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CONTENTS

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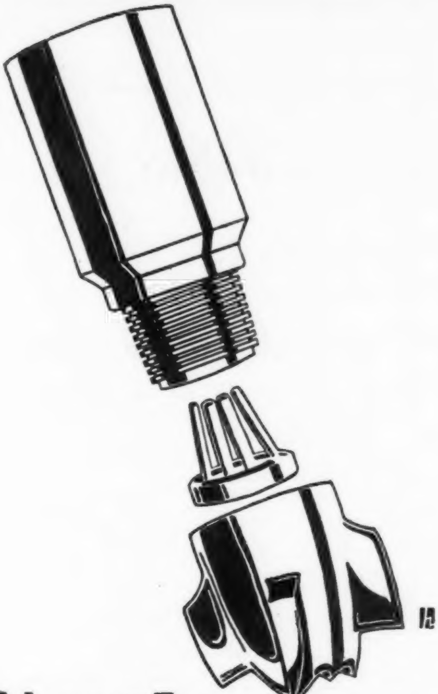

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Vol. 12 | AUGUST 1928 | No. 8

CONTENTS

Articles Scheduled for Publication in the September *Bulletin*

Gravity Anomalies and Petroleum Exploration

By M. K. HUBBERT and FRANK A. MELTON

Factors Affecting the Color of Sedimentary Rocks

By DILWORTH S. HAGER

Research and the American Association of Petroleum Geologists

By K. C. HEALD

Volume 12 Number 8

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of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

AUGUST 1928

THE CARBON-RATIO THEORY IN THE LIGHT OF HILT'S LAW[1]

FRANK REEVES[2]
Washington, D. C.

ABSTRACT

The principal tenets of the carbon-ratio theory are (1) that the chief agencies in the chemical transformation of carbonaceous deposits, after they have passed through the biochemical stage, are the pressure and the heat derived from horizontal thrust; (2) that as the coals decrease in volatile constituents the oils show a corresponding increase in the lighter and more volatile hydrocarbons, so that low-grade oils are associated with low-rank coals and high-grade oils with high-rank coals; and (3) that where the coals have reached the stage of devolatilization at which their content of fixed carbon constitutes about 65 per cent of their total combustible matter the oils in the coal-bearing and underlying formations have been converted into gases, and where the state of devolatilization is slightly higher the gases have been eliminated.

Inasmuch as a series of coals increases in percentage of fixed carbon with stratigraphic depth in both disturbed and undisturbed areas, and this increase is many times greater than any recorded increase in the horizontal direction, the writer is led to conclude (1) that the geologic agencies producing the chemical transformation of carbonaceous deposits are not so much the heat and pressure incident to horizontal thrust as the heat and pressure incident to depth of burial; and (2) that there is no clear evidence that incipient alteration of sediments has been a factor in determining the extent of our known oil and gas fields and therefore that carbon ratios of coals furnish no information as to the oil possibilities of an area.

INTRODUCTION

It is wise, as facts accumulate in any field of science, to pause from time to time in order to review our fundamental concepts, for, although these concepts may have been presented initially only as working hypotheses, there is a tendency to accept as established those that appear

[1]Manuscript received by the editor, April 19, 1928. Published by permission of the director, U. S. Geol. Survey.

[2]U. S. Geol. Survey. Introduced by J. P. D. Hull.

to explain existing relations at a stage when we should still be testing them. The writer feels that this tendency exists as to the concepts announced by David White[1] in 1915, which constitute what is commonly referred to as the carbon-ratio theory. He desires, therefore, to present what appear to him to be valid objections to the concepts. Whether geologists accept the conclusions hereinafter to be set forth or not, it is hoped that they may at least be stimulated to scrutinize critically all facts that bear upon the carbon-ratio theory rather than merely to seek to interpret these facts in conformity with it.

The hesitation that one naturally feels in suggesting a review of the widely accepted tenets of the theory in question has been lessened by David White's characteristically generous and scientific attitude toward the endeavor. He has read this paper in manuscript form, and, although he does not accept its conclusions, he approves of its publication.

The task of re-opening the question of the validity of the theory has been further lessened by the objections to its acceptance raised by Tarr[2] and Dorsey,[3] who were the first American geologists to question the tenets of the theory in print. The valid criticisms offered by these geologists do not, however, seem to promise any important change in attitude toward the theory, because the authors do not question the criteria or the theoretical assumptions upon which the theory is based. In the following paragraphs the writer will briefly outline the basis of his criticism of the carbon-ratio theory.

An examination of the tenets of the theory, as stated in the abstract of this paper, will show that a fundamental element in White's concept of the relations between carbon ratios of coal and the existence of oil and gas is the idea that the alteration of coals is due primarily to tectonic forces—that is, horizontal thrust—and that the most significant increase in the carbon ratios of coal will be found in a horizontal direction toward the region where those forces were most intense, and not vertically under stratigraphic load in accordance with the law of Hilt. The writer, on the contrary, believes that the available data indicate that the increase in carbon ratios in the vertical direction, or with stratigraphic depth, is so much greater than in the horizontal direction that the horizontal increase is a relatively negligible quantity. For example, in the Appalachian oil fields individual coal beds show an increase in carbon ratios

[1]David White, "Some Relations in Origin between Coal and Petroleum," *Jour. Washington Acad. Sci.*, Vol. 5 (1925), No. 6, pp. 189-212.

[2]R. S. Tarr, *Oil and Gas Jour.*, Vol. 24, No. 30 (December 17, 1925), p. 51.

[3]G. E. Dorsey, "The Present Status of the Carbon Ratio Theory," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 5 (May, 1927), pp. 455-63.

of but 6 to 8 per cent across the entire field, in a distance of 60 to 80 miles, whereas the same increase is attained with stratigraphic depth in 1,000 to 1,200 feet. If this increase in the carbon ratio of coals with stratigraphic depth is ignored and isocarb maps are drawn upon the coals mined around synclinal basins, such as those in which the Mid-Continent and Appalachian oil fields lie, it is obvious that although these maps will show an increase in the carbon ratios toward the bordering structural uplifts, the explanation is simply that successively deeper and more altered coals rise to the surface as the uplifts are approached (Fig. 5). Even if the included coals showed an increase away from the uplift, the aggregate effect of using different coal beds would be an increase toward the uplift. Maps so drawn have been accepted as showing the extent to which rocks are altered in different areas, whereas they show merely the degree of alteration of rocks that through the chain of geologic events happen to be now at the surface.

Even isocarbs that show the variation in rank of a single coal bed do not indicate the stage of alteration of oil sands several hundred feet above or below the coal bed. In other words, instead of the boundary between rocks of different degrees of alteration being a vertical plane whose intersection with the surface coincides with the isocarb lines, it is more nearly a horizontal plane. In the following paragraphs data that appear to the writer to substantiate these statements will be presented, and the validity of the tenets of the carbon-ratio theory will be examined in the light of the actual variation in the degree of alteration of the coals. Readers acquainted with the literature on carbon ratios will recognize that the writer is applying to a conformable series the principle which Fuller[1] suggested should be considered in dealing with a non-conformable series, namely, that the degree of alteration of the oil sands is higher than that of the overlying coal beds.

HILT'S LAW

Widespread acceptance.—The principle that a series of coals increases in degree of carbonization with stratigraphic depth was first enunciated by Hilt[2] in 1873 and has been found to apply so generally to most of the carboniferous coal fields of the world that it is spoken of as the law of

[1]M. L. Fuller, "Carbon Ratios in Carboniferous Coals of Oklahoma and Their Relation to Petroleum," *Econ. Geol.*, Vol. 15 (1920), No. 3, p. 227.

[2]Carl Hilt, "Die Beziehungen zwischen der Zusammensetzung und den technischen Eigenschaften der Steinkohlen," *Zeitschr. des Ver. deutscher Ingen.*, Band 17 (1873), Heft 4, pp. 194-202. "Des rapports existant entre la composition des charbons et leurs propriétés industrielles," *Revue Univ. Mines*, tome 35 (1874), 2e livr., pp. 389-401.

Hilt. Briggs[1] states that the law holds for the coal fields of South Wales, Kent, and the Scottish district of Sterlingshire and Lanarkshire, where the subject has been investigated; that in the great Donetz field of Russia the coals show both a variation in carbon content along their strike and a change toward anthracite in depth; and that in many places in the Suchensky coal field of Siberia the lowest seams are anthracite. According to van der Gracht,[2] the law applies to the coals encountered in the borings in the southern part of the Netherlands and northern Belgium, and Stainier[3] cites a mass of data which show that it holds for the coal fields of Westphalia, France, and Belgium.

In the United States the vertical variation in the carbon content of the coal has received less attention than in Europe, mainly because shaft mining of coal to great depths is not common. White,[4] however, has shown that the law holds for the coals in the Appalachian fields. Although there is little reliable information on the subject in the other American Carboniferous coal fields, there seems to be no reason for doubting that all Carboniferous coals illustrate the principle. Whether younger coals also show an increase in carbonization with depth has not been so definitely determined, because of lack of data.

Most writers on the carbon-ratio theory are cognizant of Hilt's law. White discussed it at length in a paper on the origin of coal that appeared before the presentation of the carbon-ratio paper. But he seems to have practically ignored the law both in considering the relationship between carbon ratios and the occurrence of oil and in the construction of isocarb maps, for several coal beds having a wide stratigraphic range were used in the construction of his map, and he did not attempt to make the necessary correction so that the map would show the variations in rank in one coal bed. In this neglect of the quantitative importance of Hilt's law he has been followed by the other geologists who have written on the subject, with the exception of Moulton,[5] who, in compiling an isocarb

[1] H. B. Briggs, "Vertical and Lateral Variations in the Composition of Bituminous Coal Seams," *Collier Guardian*, Vol. 125, No. 3259 (June 15, 1923), pp. 1507-08.

[2] W. A. J. M. van Waterschoot van der Gracht, "The Deeper Geology of the Netherlands and Adjacent Regions, with Special Reference to the Latest Borings in the Netherlands, Belgium, and Westphalia," *Government Inst. Geol. Expl. Netherlands, Mem. 2* (1909), pp. 113-18.

[3] X. Stainier, "Des rapports entre la composition des charbons et leurs conditions de gisement," *Annales des mines de Belgique*, tome 5 (1900), 4e livr., pp. 402-17.

[4] David White, "The Origin of Coal," *U. S. Bur. Mines Bull. 38* (1913), pp. 125-27.

[5] G. F. Moulton, "Carbon Ratios and Petroleum in Illinois," *Illinois Geol. Survey Rept. Investigation No. 4* (1925), pp. 9-10.

map of the Illinois coal fields, made the necessary correction to show the variation in carbon ratios of one coal bed. Fuller was the first to point out that the recognition of Hilt's law requires some modification of the use of carbon ratios in the search for oil—for example, that oil should be found in shallow sands farther in the direction of regional increase in carbonization of coals than in deep sands. But he, like the other writers on the subject, did not inquire whether the tenets of the carbon-ratio theory are substantiated by observational data when those data are viewed in the light of Hilt's law.

Not only is it widely accepted that the carbon ratios of a series of coals increase with stratigraphic depth, but there is considerable evidence that the carbon content of individual coals also increases with present depth of cover. That such a variation exists in the Carboniferous coal of Europe is widely recognized by the European coal engineers, who, because of the great depths at which their coals are mined, have precise data available on the subject. The reader will find some of these data presented in reports and papers by Stainier,[1] Pernet,[2] de Macar,[3], and Cornet.[4] In the American Carboniferous fields there are fewer data available on the subject, because as yet the coals are not mined very far back of their outcrops. But it may be pointed out that in southern West Virginia the carbon ratios of the Pocahontas No. 3 coal increase 5 to 8 per cent as it dips westward toward the center of the coal basin. There is also some evidence that the Pittsburgh coal in the northern part of the state increases slightly in fixed-carbon percentage northwestward as far down its slope as it has been mined.

This variation in fixed-carbon percentage of individual coals with present depth of cover suggests that the chemical transformation of the coals has been in progress ever since their deposition. But the fact that coals show an increase in degree of carbonization with stratigraphic depth both where they are mined in shafts and where, because of folding, they crop out on a peneplain surface, indicates that the major part of the transformation took place shortly after the deposition and deformation of the coal measures. If these conclusions are correct, it follows that the increase in degree of carbonization of a series of coals per unit

[1] *Op. cit.*, pp. 418-21.

[2] A. Pernet, "Sur la composition des couches du charbonnage de Haine-Saint-Pierre," *Pub. Soc. anciens élèves de Mons*, tome 14 (2e sér.), p. 54.

[3] J. de Macar, "Des relations entre la composition et le gisement des charbons du Bassin de Liége," *Annales Assoc. Ing. Liége*, 1876, p. 57.

[4] F. Cornet, "Discussion sur le grisou," *Soc. anciens élèves de l'École des mines du Hainaut proc. verbaux*, 1867, pl. 32.

of stratigraphic depth is considerably greater than the increase in fixed-carbon percentage of an individual coal bed per equivalent unit of depth of cover.

Quantitative importance of Hilt's law.—The precise increase in carbon ratios of a series of coals with increase in stratigraphic depth in any particular field is difficult to determine because of the rarity of localities where two or more coal beds are mined together, the scarcity of analyses, the unreliability of the analyses available (due to improper or careless sampling and lack of standardization in making the analyses), and the variations in the different coal beds due to factors other than depth. Despite these difficulties, we have sufficient data on the amount of vertical variation in the chemical character of the coals to arrive at a fairly definite and trustworthy figure for the average increase in the carbon percentages of Carboniferous coals per 100 feet of depth. Inquiry into the subject is here confined to the bituminous and semi-bituminous coals of Carboniferous age, which furnish the most data bearing upon the carbon-ratio theory. Numerous data on the subject are available in the European coal fields, where the coals are being mined at depths down to 3,000 feet or more and where the increase in carbonization with depth has received precise study by a number of geologists and coal engineers, among whom may be mentioned Hilt, Stainier, van der Gracht, Strahan, and Galloway. The results of some of these investigations have been summarized by White,[1] and the writer, for the sake of brevity, will confine his presentation of the data from the European fields mainly to White's summary, adding only the data recently made available by the deep borings in Kent, England.

TABLE I

INCREASE IN FIXED-CARBON PERCENTAGE OF EUROPEAN COALS OF CARBONIFEROUS AGE PER 100 FEET OF DEPTH

Coal Field	*Increase in Fixed-Carbon Percentage per 100 Feet of Depth (Moisture and Ash Excluded)*
Kent	0.57
South Wales	0.60
Netherlands	0.66
Westphalia { gas coal	0.51
Westphalia { coking coal	0.71
Average	0.61

[1]David White, "The Origin of Coal," *U. S. Bur. Mines Bull. 38*, 1913, pp. 126-27.

The amount of increase in fixed-carbon percentage of the coals in the United States was studied about 20 years ago, also by White,[1] who obtained an average figure of 0.38 per cent increase per 100 feet. However, he stated that this low value is probably due to the fact that several analyses of canneloid coals were compared with analyses of overlying coals containing no canneloid matter.

The writer has compiled the data embodied in Table II from localities in the central part of the Appalachian coal basin. With few exceptions the coals used in determining the increase in carbon percentage with depth are mined either in the same shaft or in the same locality.

The average increase in the carbon percentages per 100 feet for all the localities is 0.69 per cent, the range being 0.27 to 1.91. The greatest variation occurs in the coals in localities 11 to 17, which are separated by the smallest interval and where, consequently, slight variation in their composition due to factors other than depth would somewhat obscure the variation due to depth. If these localities were excluded the average increase per 100 feet would be 0.53 per cent. But as variations are as likely to occur in one direction as another, we are scarcely justified in excluding these from consideration, and consequently the average of 0.69 per cent may be allowed to stand. This is close to the average of 0.61 per cent for the European Carboniferous coals. Considering the great number of analyses used in these computations, the number of fields represented, and the consistency of the data, it seems justifiable to assume that the average normal downward increase in the carbon percentages of Carboniferous bituminous and semi-bituminous coals is at least 0.6 per cent per 100 feet.

The objection may be raised that although carbon ratios increase at this rate for the first few hundred feet, there is doubt whether they would continue to increase at this rate at greater depths. Yet, inasmuch as the factors of earth temperature and pressure, which probably cause these increases, vary regularly down to depths of at least several thousand feet, there is no reasonable basis for the assumption that the rate of increase is not maintained until a coal with the rank of anthracite is produced. Apparently increase of depth of cover offers no difficulties to the escape of volatile constituents, thereby retarding the devolatilization of the coals, for if it did, its effect would be apparent in the first few hundred feet of cover. Whatever may be true at depths of several miles, coals encountered in deep borings show as great an increase in carbon ratios at depths of 3,000 to 4,000 feet as at shallower depths. For ex-

[1] *Op. cit.*

TABLE II

INCREASE IN FIXED-CARBON PERCENTAGE OF COALS WITH DEPTH IN THE CENTRAL PART OF THE ALLEGHENY COAL BASIN

Locality	*Coal Bed*	*Number of Samples*	*Carbon Ratio*	*Difference in Percentage of Fixed Carbon (Ash and Moisture-Free Basis)*	*Stratigraphic Interval (Feet)*	*Increase in Carbon Percentage per 100 Feet (Per Cent)*
1. Southeastern Guernsey County, Ohio[3]	Pittsburgh Upper Freeport	4 9	52.0 59.0	7	500	1.40
2. Welch, W. Va.[2]	Welch Pocahontas No. 3	6 2	79.2 82.8	3.6	800	.45
3. Newburg, W. Va.[1]	Pittsburgh Lower Kittanning	2 2	64.5 67.6	3.1	800	.38
4. Rosemont, W. Va.[3]	Pittsburgh Upper Kittanning	10 3	58.9 64.0	5.1	800	.64
5. Thomas, W. Va.[3]	Lower Pittsburgh Upper Freeport	2 18	72.3 75.4	3.1	740	.44
6. Gates, Pa.[2]	Waynesburg Pittsburgh	4 1	63.6 61.5	2.1	350	.60
7. Dunbar, Pa.[2]	Waynesburg Lower Freeport	3 7	60.5 65.6	5.1	1000	.51
8. Uniontown, Pa.[2]	Sewickley Upper Freeport	3 4	62.8 66.4	3.6	750	.48
9. Rice's Landing, Pa.[2]	Waynesburg Pittsburgh	5 1	58.7 60.6	1.9	350	.54
10. Elk Lick, Pa.[2]	Pittsburgh Lower Freeport	9 5	76.75 79.30	2.65	600	.44
11. Fairmont, W. Va.[1]	Sewickley Pittsburgh	2 2	57.7 60.0	2.3	120	1.91
12. New Geneva, Pa.[1]	Sewickley Pittsburgh	5 7	59.54 60.08	.54	150	.36
13. Meyersdale, Pa.[2]	Redstone Pittsburgh	13 11	76.77 77.07	.30	80	.37
14. Rockwood, Pa.[2]	Upper Freeport Lower Kittanning	4 6	76.3 76.57	.27	100	.27
15. Gray's Landing, Pa.[2]	Sewickley Pittsburgh	6 3	59.8 61.6	1.8	150	1.20
16. Frostburg, Md.[1]	Tyson Pittsburgh	8 17	80.67 82.27	1.5	120	1.25
17. Davis, W. Va.[3]	Bakerstown Upper Freeport	14 27	72.8 74.9	2.1	180	1.15
Average increase per 100 feet						.69

[1]Shaft mine. [2]Coals mined in same locality. [3]Coals mined in adjacent localities.

ample, the graph compiled by Galloway[1] showing the increase in carbonization of the numerous coal beds encountered in deep borings in Kent, England, is very nearly a straight line, the increase in carbon content being as great at depths of nearly 4,000 feet as close to the surface. It appears justifiable, therefore, to assume that in any region where the carbon ratios of the surface coals are 60 per cent, the degree of alteration of the sediments at depths of 4,000 to 5,000 feet would be that represented by coals with carbon ratios of 85 to 90 per cent.

The different tenets of the carbon-ratio theory will now be examined in the light of the data that have been presented.

TENETS OF THE CARBON-RATIO THEORY

I. THRUST-PRESSURE HYPOTHESIS

Horizontal thrust as a factor in the chemical transformation of coal.—In most papers on the carbon-ratio theory there is a tendency to attribute most of the variation in ranks of coal to the effect of heat and pressure incident to horizontal thrust.[2] The writer does not deny the possibility that this cause may have contributed to the chemical transformation of carbonaceous deposits. He desires to point out, however, that the facts that Hilt's law appears to hold for practically all coals, in both disturbed and undisturbed coal basins, and that the rank of individual coal beds varies with depth of cover may be reasonably interpreted as indicating that the carbonization of coals is brought about mainly by the heat and pressure incident to the burial of the coals. That deformation of coal-bearing rocks may increase earth temperature and consequently be an added factor in the carbonization of coals is, of course, a possibility. The carbonization of coal by deformation is, however, not accepted by European geologists, because, as Stainier[3] shows, in the Westphalian and French-Belgian coal fields the coal beds are richer in volatile matter on the south side of the coal basin, where the coal measures are highly folded and faulted, than they are on the north side, where the strata

[1]W. Galloway, "On the Origin of Anthracite," *Proc. South Wales Inst. of England*, Vol. 37, No. 5 (1921), p. 401.

[2]In a recent article entitled "Quelques relations entre les charbons de différentes espéces et la composition des dépôts sédimentaires originels (extrait du *Livre Jubilaire* publié á l'occasion du cinquantenaire de la fondation de la Société géologique de Belgique)," 1926, pp. 9-10, White states that the temperature to which the coals have been subjected is that due to their depth of burial, augmented by the heat resulting from the deformation of the strata and the chemical reactions in the coals.

[3]X. Stainier, "Des rapports entre la composition des charbons et les conditions de gisement," *Annales des mines de Belgique*, tome 5 (1900), 4e livr., pp. 532-33.

are much less disturbed. Of course, in many fields, such as the Appalachian region and the Arkansas coal field, the rank of individual coals in general increases in the direction of increasing deformation, but there is the probability that this increase, as Lesley[1] suggested, may be due to an increase in the depth of burial because of regional thickening of the coal measures. At any rate, there are sufficient difficulties in the way of the acceptance of the thrust-pressure hypothesis as an explanation of the variation in rank of the coals to prevent Lesley and Stevenson,[2] two former eminent students of the Appalachian coals, from accepting the hypothesis. The seriousness of these objections is evident from the following statement by White:[3]

> [The thrust-pressure hypothesis] has been advanced by a number of field geologists who have studied coal fields to which no other theory seemed applicable. Yet it has in general been rejected, even by those who at first advocated it, on account of the seeming importance of certain supposedly conflicting facts, so that there are few, except among American geologists, who are convinced of its adequacy and validity, and fewer still who agree that it is the principal agency through which most of the high-grade coal of the world has been transformed from peat.

White stated, however, that these seemingly adverse facts, when properly interpreted, corroborate rather than contradict the hypothesis, for he holds that folds and faults compensate and relieve the pressure to which the coals are subjected, and therefore the carbonization of coals in highly folded or faulted areas may be less than in adjacent areas of no deformation, where the pressure continues for a long period without relief.

The validity of this interpretation will be briefly considered, for it is encountered in most discussions by American geologists of variation in the rank of coals. In the first place, it must be obvious that the reasoning allows a considerable degree of freedom for the interpretation of geologic data that bear on a disputable subject, for it permits its proponents to consider intense folding and faulting as evidence either of intense stress or of relief of stress, the application depending on which interpretation fits the field data.

[1] J. P. Lesley, "Note on the Classification of Coals," in *Second Report of Progress in the Laboratory of the Survey*, by A. S. McCreath, *Pennsylvania Second Geol. Survey* 1879, pp. 155-56.

[2] J. J. Stevenson, "Origin of the Pennsylvania Anthracite," *Bull. Geol. Soc. Amer.*, Vol. 5 (1893), pp. 39-70.

[3] David White, "The Origin of Coal," *U. S. Bur. Mines Bull. 38* (1913), p. 105.

Furthermore, a brief consideration of the mechanics of folding and faulting makes it apparent that the interpretation may be questioned, for although it is true that the bending or rupturing of a beam subjected to endwise pressure relieves the stress in the beam and that thereafter such a beam can not offer the resistence necessary for the accumulation of stress, yet when a segment of the earth's crust is subjected to horizontal pressure, folding and faulting do not necessarily relieve the internal stress, because the force opposing the pressure is not so much the crushing or bending strength of the rocks as the frictional resistance inherent in the deformation of great masses. This resistance may actually increase with the displacement and piling up of the strata, the formation of the folds and faults representing an incident in the growth of the stress rather than its culmination. It is obvious that if this were not true deformation by horizontal pressure would result in the formation of one fold or overthrust rather than a number of folds and thrust faults, such as are characteristic of the major mountain systems of the world. Whether or not these statements are fully conceded, it must be evident that if heat and pressure incident to horizontal thrust are potent factors in the chemical transformation of carbonaceous deposits, the effect will be greater in a folded and faulted area than in an adjacent belt of no deformation, irrespective of the competency of the rocks in the two areas, because in a disturbed area the coals may be subjected to squeeze on the limbs of the folds, and the slipping and bending of the rocks may conceivably generate sufficient heat to raise the normal earth temperature, whereas in an undisturbed area sandstones and other resistant members of the coal measures protect the coals from the full force of the pressure and, there being practically no movement, no heat is generated.

White, in considering the evidence for his hypothesis, does not discuss the possibility that the low rank of coals near faults may be due to their stratigraphic position or past depth of burial. For example, he attributes the fact that the carbon ratios of the coals in the Broad Top field of eastern Pennsylvania are 10 to 15 per cent lower than those in the anthracite field, on the northeast, and 2 to 3 per cent lower than those in the Windber district, 25 miles farther west, to the relief afforded by the large overthrust bordering the Broad Top field,[1] yet it appears more probable that the difference in rank of these coals is due to the fact that the coal measures in the Broad Top field are only 20 to 30

[1]David White, "Progressive Regional Carbonization of Coals," *Trans. Amer. Inst. Min. and Met. Eng. Preprint 1414 I* (February, 1925), p. 13.

per cent as thick as those in the anthracite field and 80 to 90 per cent as thick as those in the Windber district. He also attributes the decline in carbon ratios southwestward from Pocahontas, in northern Tazewell County, to St. Paul, in eastern Wise County, Virginia, shown by Eby's map,[1] to the compensating effect of an overthrust fault that has its beginning near Pocahontas and gradually increases in amount of overthrust toward St. Paul[2] (Fig. 4), and he does not mention the possibility that the decline in carbon ratios in this direction shown by the map may be due to the fact that progressively younger coals are mined in going southwestward along the fault. The Jawbone bed, mined near St. Paul, is 1,600 feet higher in the stratigraphic series than the Pocahontas No. 3 bed, mined at Pocahontas. Coals mined between these two localities occupy intermediate stratigraphic positions. The fact that carbon ratios of the coals in Wise and Lee counties, in southwestern Virginia, are 15 to 17 per cent lower than the coals on the northeast, in southern West Virginia, is also attributed to compensating effects of the great overthrust faults in southwestern Virginia, and apparently no consideration is given to the difference in stratigraphic position of the coals in the two areas. Yet the coals mined in southern West Virginia belong to the Lee formation, and those in Wise and Lee counties to a younger series of coal measures in the Wise formation. The stratigraphic interval between the coals in the two areas ranges from 2,500 to 3,000 feet. When the fact is taken into consideration that the Carboniferous coals show an average increase in carbon ratio of 0.6 per cent per 100 feet in stratigraphic depth, and the proper corrections are made so that the isocarbs indicate the rank of one coal bed, it will be found that the carbon-ratio "highs" and "lows" of which Eby[3] speaks disappear.

In the light of the facts set forth it appears evident that in discussions as to the variations in rank of coals in a region, the hypothesis that these are due to differences in intensity of deformation should not be accepted without the consideration of other possible causes, and at least the fact of the variations should be established by a study of individual coals.

Horizontal thrust as a factor in the chemical transformation of oil.— That the grade of oil is increased by the heat and pressure incident to

[1] J. B. Eby, "The Possibilities of Oil and Gas in Southwest Virginia as Inferred from Isocarbs," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 4 (July-August, 1923), Fig. 1, p. 423.

[2] David White, *op. cit.*, p. 14.

[3] *Op. cit.*, p. 424.

horizontal thrust is even less certain than that the rank of coal is affected by these agencies. Oil, being a fluid and occupying the porous parts of rocks, can scarcely have been subjected to the pressure exerted by horizontal thrust. Moreover, if the heat and pressure due to horizontal thrust were the principal factors in the chemical transformation of oils, seemingly it should follow that the oils would be highest in rank and grade in the region where the formations are most deformed, irrespective of their age. Yet most of our high-grade oils are the Paleozoic oils of the Appalachian and Mid-Continent fields, where the strata are practically undisturbed, whereas many low-grade oils come from highly deformed Tertiary beds. There is little evidence that oils in individual oil sands increase in rank toward areas of increasing deformation. White's original isocarb map[1] showed an increase in grade toward the southeast both for the Kansas-Oklahoma fields and for all the fields in the eastern part of the United States. Later development has shown that the oils of Kansas and Oklahoma do not increase in grade toward the southeast. If any generalization can be made as to the grade of the oils it is that the deeper sands yield the highest-grade oil and the oil of individual sands is highest in grade in the fields where the sand is encountered at the greatest depth. As to the variation in grade of oil in the Appalachian fields, White's map gives the impression that there is progressive increase in the grade of oils from the Illinois field eastward to and across the Appalachian fields, for it shows a gravity of 30° Bé. for the Indiana-Illinois fields, 40° for the central Ohio fields, and 45° for the Appalachian fields. These oils, however, are so widely separated as to geographic position and geologic age that the assumption that the grade of each is determined by its proximity to the Appalachian Mountains is scarcely justified. If oils from the individual sands in the different fields showed an increase in grade toward the east, then it would be more reasonable to assume that proximity to the disturbances in the Appalachian belt was responsible for the increase in grade of oil. Yet there is no evidence that this is true in the Illinois, Indiana, and western Ohio fields, and there is no definite proof that it is true in the Appalachian fields. Whatever evidence there has been in the past to support the generalization that the grade of oil increased toward the east probably arose from the fact that in general the producing sands in the eastern part of the Appalachian field are older and lie at greater depths than those in the western part of the field. The fact that there is a belt east of the oil-producing areas in which gas alone is found does not necessarily imply that the distillation

[1] *Jour. Washington Acad. Sci.*, Vol. 5, (1915) No. 6, Fig. 1, p. 199.

of the organic débris there has reached a more advanced stage than in the oil fields farther west, for it should not be forgotten that gas fields commonly border oil fields on the up-dip sides of synclinal basins, both on the side toward which the coals become progressively lower in rank and on the side toward which they become higher in rank. For example, the large "Clinton sand" gas field in central Ohio lies up the dip from, and west of, the oil-producing belt in the same sand and in the direction toward which the coals become lower in rank (Fig. 4). Other reasons for not regarding gas as proof of an advanced stage in the distillation of the oil have been cited by Dorsey.[1]

2. CORRESPONDENCE IN RANK AND GRADE OF ASSOCIATED COALS AND OILS

Although it is doubtful whether the heat and pressure incident to horizontal thrust are the principal agencies in the chemical transformation of coals and oils, the tenet that associated coals and oils should show a correspondence in rank and grade appears to be sound, for if the chemical transformation of carbonaceous deposits is principally a geologic process, this would appear to be consistent with the theory, no matter what the geologic processes are. Furthermore, as White points out, it is in fairly close accord with the observational data in many oil fields. That there are many exceptions to it is undoubtedly true, but this is probably due to the fact that oils may deteriorate in grade as the result of escape of their volatile constituents and the chemical changes brought about by contact with sulphate- and oxygen-bearing ground waters.

3. CORRELATION OF DEGREE OF CARBONIZATION OF COALS WITH OCCURRENCE OF OIL AND GAS

Theoretical basis for the correlation.—The hypothesis that oil is eliminated from rocks when the carbon ratios of associated coals reach 65 or 70 per cent and that gas also is driven out at a slightly higher stage in the alteration of the sediments rests essentially on a basis of observation. At any rate, it does not appear to be a conclusion that would be deduced from theoretical considerations. In the first place, it can scarcely be inferred that carbonaceous deposits from which oil and gas are distilled would cease to yield distillates while the associated coals were still yielding volatile compounds, especially as the canneloid coals, which are more closely related to the mother rocks of petroleum than other coals, are even richer in volatile compounds. Neither can it be inferred that the oil and gas already distilled would be eliminated from the porous parts of the rocks at this stage in the alteration of the sediments. White's

[1] *Op. cit.*, pp. 461-62.

concept is that the oils are converted into gases at this stage, but just how the gases are to be eliminated at a slightly higher stage is not clear. The implication is that the rocks are so broken up by folding and faulting that the gas escapes. But the correlation of degree of alteration with intensity of deformation is not as simple as this, for degree of alteration may be dependent upon other factors as well as upon intensity of deformation. The data presented under the discussion of Hilt's law indicate that depth of burial without deformation may bring about the same degree of alteration of sediments as that attained in some areas of considerable disturbance—for example, the anthracite fields of Pennsylvania and Arkansas. The elimination of gas may be accomplished by factors entirely unrelated to degree of alteration, such as circulation of ground water and proximity to outcrop. If such factors eliminate the gas it seems probable that they may eliminate the oil also. At any rate, the concept that the oils are eliminated by being volatilized encounters difficulties, for although the production of lighter and more volatile hydrocarbons might result in a diminution in the volume of the oil, the residue, as in the case of the coals, would become increasingly rich in non-volatile compounds, which could not be eliminated by the heat and pressure to be expected in the incipient stages of metamorphism. Consequently, from whatever angle the subject is approached, the postulate that the oil and gas are eliminated at a particular stage in the alteration of the sediments is beset with difficulties. Russell,[1] in a recent article, has attempted to find a way out of these difficulties by suggesting that the disappearance of the oil and gas may be due to the induration of the rocks and the consequent loss of pore space. The only possibility, as it seems to the writer, of demonstrating that the occurrence of oil and gas is related to the degree of alteration of sediments lies in such an explanation as this, for it is difficult to understand in what other way moderate heat and pressure could be effective in removing fluids and gases from rocks. However, inasmuch as it is generally conceded and is admitted by Russell[2] that conditions entirely unrelated to degree of metamorphism may be the dominant factors in determining the porosity of rocks in the incipient stage of metamorphism, there appears to be no theoretical basis for the assumption that formations with which coals of sub-bituminous or anthracite rank are associated contain no porous

[1]W. L. Russell, "The Proofs of the Carbon-Ratio Theory," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 9 (Sept., 1927), pp. 981-83.

[2]W. L. Russell, "Porosity and Crushing Strength as Indices of Regional Alteration," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 10 (Oct., 1926), p. 945.

beds, and it need only be pointed out that in the Appalachian region deep wells drilled along the eastern margin of the field penetrated sands at depths of 5,000 to 7,000 feet that were porous enough to yield gas and great volumes of water. Again, in the unproductive areas east of the Mid-Continent field, where the surface coals attain a carbon ratio exceeding 80 per cent, the formations, as Croneis[1] shows, contain porous sands that yield both water and gas.

Field evidence upon which the correlation is based.—The field evidence that has been presented in support of the conclusion that oil and gas are eliminated at an early stage in the alteration of the sediments may be summed up as follows. (1) Isocarb maps of the Mid-Continent and Appalachian oil fields show that the regional alteration of the sediments increases toward the southeast and that where a stage of alteration in which the coals have a carbon ratio of 60 to 65 per cent is reached no oil is found, and at a slightly more advanced stage gas also is absent. (2) No commercial oil fields in the world occur in or beneath formations in which the regional carbonization of the organic débris exceeds 70 per cent.

Evidence presented by isocarb maps.—Isocarb maps purporting to show the variation in degree of carbonization of coals in the Mid-Continent, Illinois, and Appalachian oil fields have been compiled by White,[2] Fuller,[3] Croneis,[4] Moulton,[5] Reger,[6] Semmes,[7] Eby,[8] and Russell.[9] These

[1]Carey Croneis, "Oil and Gas Possibilities in the Arkansas Ozarks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 3 (March, 1927), pp. 285-89.

[2]David White, "Some Relations in Origin between Coal and Petroleum," *Jour. Washington Acad Sci.*, Vol. 5 (1915), No. 6, Fig. 1, p. 199. "Progressive Regional Carbonization of Coals," *Trans. Amer. Inst. Min. and Met. Eng.*, Vol. 71 (1925), Fig. 1, p. 257.

[3]M. L. Fuller, "Relation of Oil to Carbon Ratios of Pennsylvania Coals in North Texas," *Econ. Geol.*, Vol. 14 (1919), No. 7, pp. 536-42. "Carbon Ratios in Carboniferous Coals of Oklahoma and Their Relation to Petroleum," *Econ. Geol.*, Vol. 15 (1920), No. 3, Fig. 34, p. 232.

[4]Carey Croneis, "Oil and Gas Possibilities in the Arkansas Ozarks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 3 (March, 1927), Fig. 2, p. 294.

[5]G. F. Moulton, "Carbon Ratios and Petroleum in Illinois," *Illinois Geol. Survey Rept. Investigation No. 4* (1925), Figs. 2 and 3, pp. 9 and 12.

[6]D. B. Reger, "Carbon Ratios of Coals in West Virginia Oil Fields," *Trans. Amer. Inst. Min. and Met. Eng.*, Vol. 65 (1921), p. 523.

[7]D. R. Semmes, "Oil Possibilities in Northern Alabama," *Trans. Amer. Inst. Min. and Met. Eng.*, Vol. 65 (1921), p. 141.

[8]J. B. Eby, "The Possibilities of Oil and Gas in Southwest Virginia as Inferred from Isocarbs," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 4 (July-August, 1923), Fig. 1, p. 423.

[9]W. L. Russell, "Relation Between Isocarbs and Oil and Gas Production in Kentucky," *Econ. Geol.*, Vol. 20 (1925), No. 3, Fig. 1, p. 253.

maps, with the exception of those that are supplanted by later ones, are reproduced in Figures 1 to 4. They therefore present the chief observational data upon which the main tenet of the carbon-ratio theory rests. Before presenting the evidence that seems to the writer to indicate that these maps do not show the degree of alteration of the oil-bearing rocks and that they therefore do not furnish an adequate basis for the correlation of degree of alteration of sediments with occurrences of oil and gas, it is desired to call attention to the fact that most of them do not even show the degree of alteration of any one coal bed. In only one of them —Moulton's map of the Illinois fields (Fig. 1)—are the carbon ratios reduced to a single coal bed. The others are based upon coals having a stratigraphic range of 2,000 to 3,000 feet, and if corrections had been made for this range so that the isocarbs would represent as nearly as possible the degree of carbonization of a single coal, some of the maps might actually have shown an increase in carbon ratios in a direction opposite to that which they now show. For example, it is probable that the carbon ratios of individual coal beds in the north-central Texas fields increase toward the west rather than toward the east, as Fuller's map shows. This map is reproduced as Figure 2, which shows also the outcrops of the coals upon which the isocarbs are based. Examination of this map shows that the 50-per cent isocarb is based upon No. 7 coal and the 60-per cent isocarb is based upon No. 1 coal. No. 7 coal lies about 3,000 feet higher in the stratigraphic series than No. 1 coal and would therefore be expected to have a lower carbon ratio. If the depth factor had been considered and the carbon percentage of No. 7 coal had been reduced to terms of the No. 1 coal by assuming an increase of 0.6 per cent per 100 feet of stratigraphic interval, the isocarbs would have shown an increase toward the west of 5 per cent rather than a decrease in that direction of 10 per cent. The coal analyses available are too few and unreliable to substantiate this conclusion, but in the light of the fact widely recognized by the coal-mining engineers of the European fields that individual coal beds increase in carbon percentage with depth of cover it is a justifiable assumption, for these Texas coals dip westward, and their cover attains a greater thickness in that direction.

A question can also be raised as to whether the carbon ratio of individual coals in the eastern Oklahoma fields rises toward the southeast, as the isocarb maps of the area show (Fig. 3), for although the coals east of the oil fields increase markedly in degree of carbonization toward the southeast, there is no proof that the coals in the oil fields increase in that direction. The increase that the maps show is largely, if not altogether,

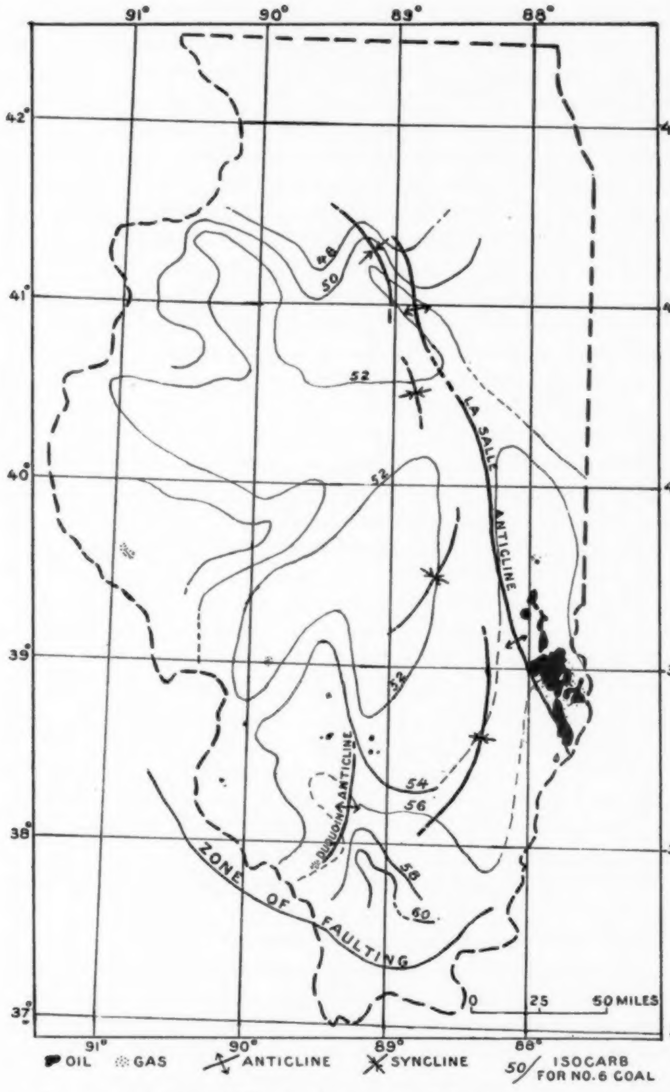

FIG. 1.—Isocarb map of Illinois, showing also anticlines and synclines. (Compiled from Moulton's maps.)

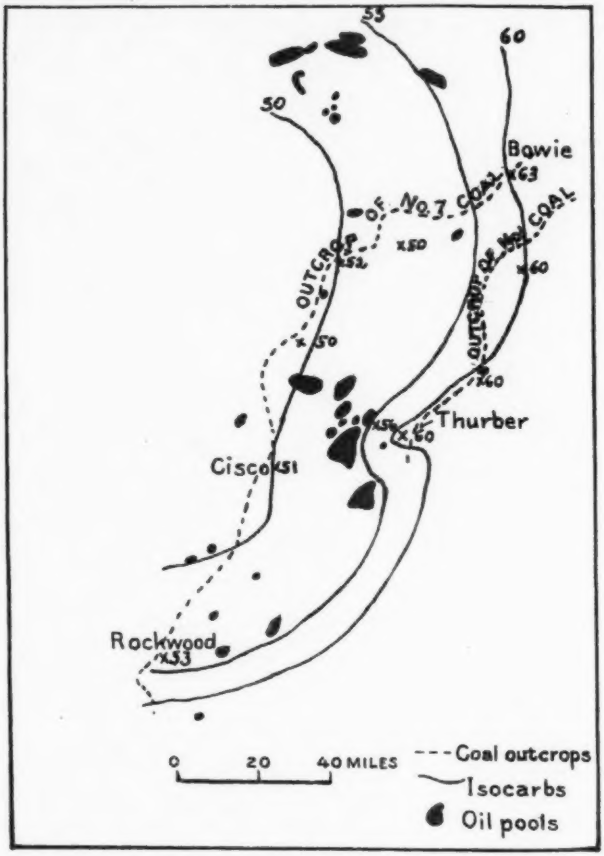

FIG. 2.—Isocarb map of north-central Texas. (After Fuller.)

due to the fact that progressively older and more altered coals rise to the surface from west to east across the oil fields. In fact, it is possible that here again the individual coal beds show a slight increase in carbon ratios toward the west, in the direction toward which their cover becomes thicker. At any rate, the Henrietta coal in the Henrietta field is reported to be of higher rank where it has been penetrated by diamond-

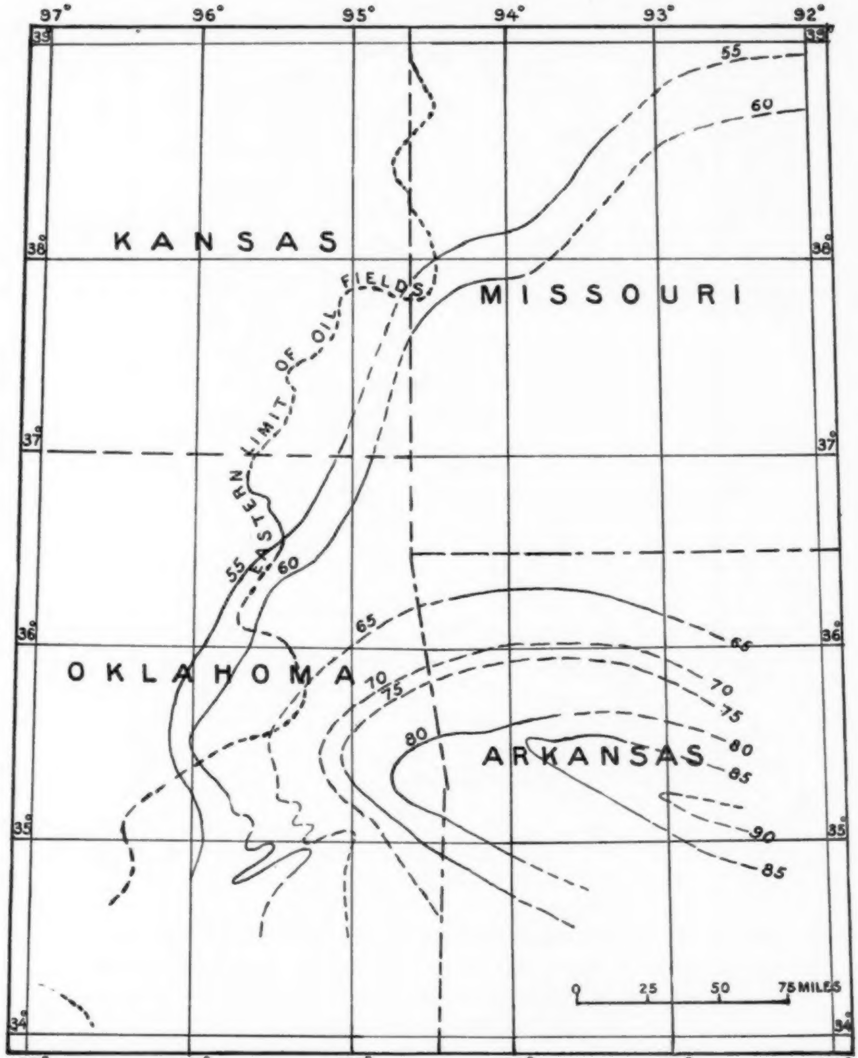

FIG. 3.—Isocarb map of the eastern Oklahoma oil fields and adjacent areas. (After Croneis.)

drill holes at depths of 500 to 600 feet than it is in the drift mines a few miles farther east.[1]

Although no reductions were applied to the isocarb maps of the Appalachian oil field so that they would depict the degree of carbonization of one coal bed, it is known that individual coal beds actually show an increase in fixed carbon toward the southeast in most districts, the only exception being possibly where their northwestward dip along the southeastern margin of the coal basin gives them an increasing depth of cover toward the northwest. But if this variation is ignored it is found that individual coals in the Pittsburgh coal basin, in which the oil fields lie, show an increase of 8 to 10 per cent in carbon ratio from their most northwesterly outcrop to their most southeasterly outcrop. The increase is an average of 1 per cent in 10 miles, or 0.6 per cent in 6 miles. Farther east the rate of increase is three or four times this, but the lower rate holds throughout the oil fields and for 10 to 20 miles east of the oil fields. Consequently, the isocarb map of the Appalachian field shown in Figure 4, which is a compilation by the writer of published maps by White, Reger, and Eby, can be accepted as indicating approximately the range in rank of one coal bed for at least the areas which contain the oil fields. But, as already stated, a map showing the carbon ratio of a coal bed furnishes no basis for the correlation of degree of alteration with occurrence of oil and gas, because it does not show the degree of alteration of the oil sands. If all the oil were found in one sand that occurred at some constant interval above or below the coal bed, then the data furnished by such a map could be used as a working hypothesis to determine the relation between degree of alteration and occurrence of oil. But this is not true for any field for which isocarb maps have been prepared, and certainly not for the Appalachian and Mid-Continent fields, where oil is obtained in a number of sands occurring at depths of 1,000 to 4,500 feet below the surface coals. In the Appalachian field, therefore, where the carbon ratios of coals increase as much in 100 feet in the vertical direction as they do in 6 miles in the horizontal direction, the degree of alteration attained by any coal on the eastern margin of the field is no greater than that attained by coals 1,200 to 1,500 feet lower in the stratigraphic series on the western margin of the field. The carbon ratio of the Freeport coal, at the western margin of the field, in southeastern Guernsey County, Ohio, lying but 500 feet below the Pittsburgh coal, is as high as the carbon ratio of the Pittsburgh coal 80 miles farther southeast and 15 to 20 miles southeast of the eastern margin of the oil fields.

[1] *Oklahoma Geol. Survey Bull. 4* (1926), p. 38.

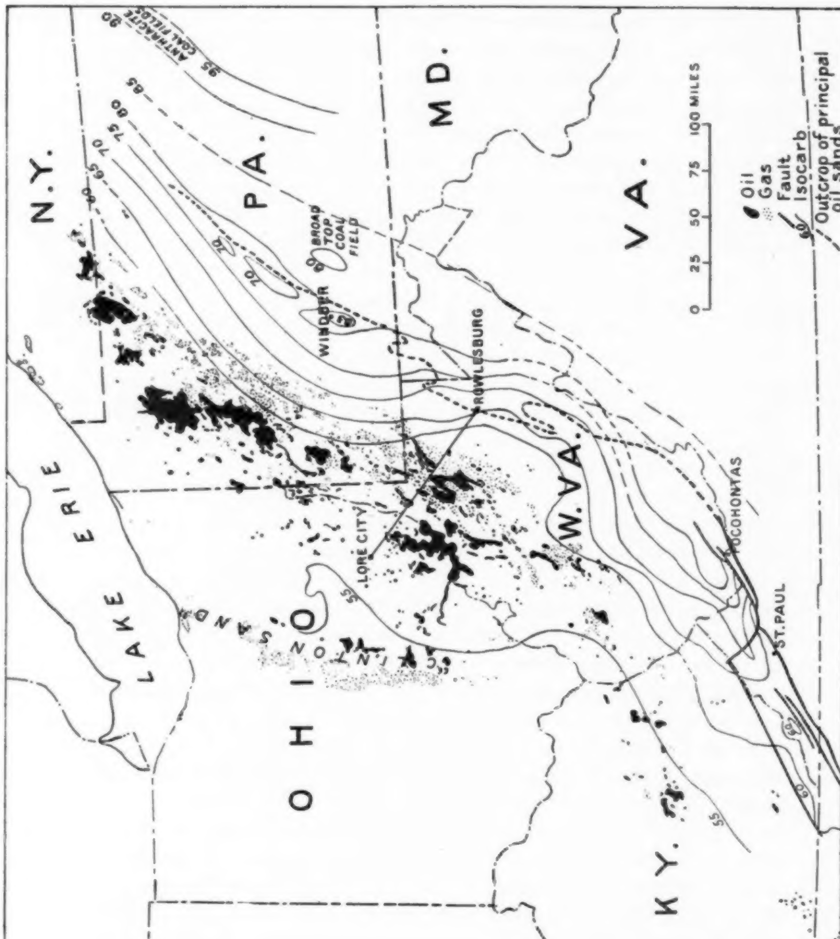

FIG. 4.—Isocarb map of the Appalachian oil fields. (Compiled from maps by White, Reger, and Eby.)

If, therefore, carbon ratios indicate the degree to which sediments are altered and if the degree of alteration determines the possibility of their yielding oil, it is evident that so far as degree of alteration is concerned the possibility of any particular sand in the barren belt east of the oil field yielding oil is as great as of a sand 500 feet below it 30 miles farther northwest, in the center of the oil field. In other words, if degree of alteration is a controlling factor in occurrence of oil, the eastern margin of production for each sand should vary with the stratigraphic depth of the sands, the shallower sands producing oil many miles farther east than the deeper sands. But there is no indication of an eastward overlapping in the production of the shallow sands. In fact, exactly the opposite situation is present, oil being found farther east in the deeper sands than in the shallow sands. In Kentucky the deeper "sands" are limestones, and Russell,[1] in noting that they yield oil farther east than the sandstone, states that the isocarb maps suggest "that oil and gas pools may occur in limestone where the regional alteration of the rocks is too high for their occurrence in sandstones." Unfortunately for this explanation, the deeper sands in West Virginia and Pennsylvania are sandstones. Obviously, the reasonable conclusion to draw from these data is that the eastern limit of production in any sand, and therefore for the field as a whole, is not related to degree of alteration.

The lack of relationship between the occurrence of oil and gas and the degree of alteration of the sediments in the central part of the Appalachian oil field is shown graphically in Figure 5. Cross sections of other fields would show the same lack. This is especially true of the Mid-Continent fields, for there the increase in carbon ratios toward the southeast, if present at all, does not exceed that of the Appalachian oil fields, and oil is found in the eastern margin of the fields at depths as great as 4,500 feet beneath the surface coals.

Proponents of the carbon-ratio theory may seek to escape the implication of the facts here set forth, by postulating either that the oil in all the sands originated from one mother rock, or that the failure of the shallower sands to produce oil farther east than the deeper sands should be ascribed to other factors than degree of alteration. But the first suggestion is a contradiction of the carbon-ratio theory, for it implies that once oil has been distilled and has migrated to porous sands, it is no longer affected nor can it be eliminated by heat and pressure. As to the suggestion that the failure of the rocks to yield oil as far east as their

[1]W. L. Russell, "The Proofs of the Carbon-Ratio Theory," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 9 (Sept., 1927), p. 254.

degree of alteration would allow is due to the absence of other favorable conditions, it is evident that wherever this interpretation has to be placed upon field data to make the carbon-ratio theory appear applicable, these data furnish no unmistakable proof of the carbon-ratio theory; and the writer urges that such a generalization as the one under consideration, which is not entirely satisfactory from a theoretical standpoint, should be fully substantiated by field data before it is accepted and before reasons are offered for its failure to conform to observed data in a particular locality.

Supporters of the carbon-ratio theory state that the geologic conditions in the area east of the producing oil belt in the Appalachian fields differ only in degree of metamorphism from those in the oil belt. This is undoubtedly true so far as our knowledge goes as to source material, reservoir rocks, and favorable structure, but they overlook what the writer believes is the most important factor other than structure to be considered in searching for oil in areas underlain by sedimentary rocks, namely, that of water flushing. Theoretically this would appear to be an important factor in determining the oil possibilities of an area, for it is widely recognized that underground waters in many regions flow slowly through sandstones and other porous beds, and it is reasonable to assume that such circulation must tend eventually to displace all oil and gas that is not securely trapped in the sands or is not in some way protected from the circulation. This assumption is supported by the fact that the Paleozoic oils are commonly found in synclinal basins where ground-water circulation has not been sufficient even to rinse out the waters buried with the sediments. Occurrence of Paleozoic oils in highly disturbed areas, such as the Turner Valley field of Alberta, may be attributable to the fact that the oil sands have been completely isolated from ground-water circulation by faulting. In fields such as those of Wyoming and Montana, where the regional structure is favorable to active circulation of underground water (proved by the fact that where not producing oil or gas the sands yield enormous flows of fresh water), the Carboniferous and older formations commonly yield tarry residues and scattered small pools of heavy oil, whereas the younger Cretaceous formations yield larger pools of higher-grade oil. With few exceptions, however, these larger pools are found only in those domes that are the most faulted and the most remote from the mountain uplifts where the sands crop out. In domes lying nearer the mountains, where geologic conditions otherwise seem as favorable for the occurrence of oil as in the more remote domes, the oil sands yield only flows of fresh water. As

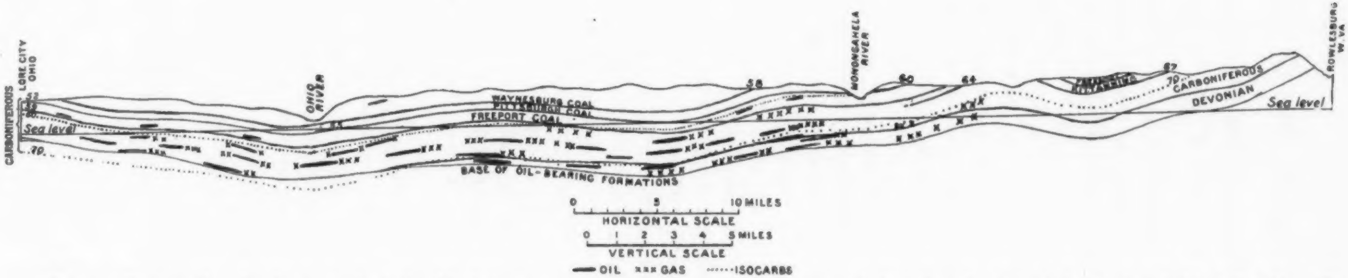

FIG. 5.—Cross section showing lack of relationship between occurrence of oil and gas and degree of alteration of sediments in the Appalachian oil fields. The position of the 70-per cent isocarb is determined from the data herein presented as to the vertical increase in carbon ratios of coal.

Rich[1] has pointed out, these facts lead to the conclusion that the absence of oil in the domes near the outcrop of the rocks in this region is due to water flushing.

In the light of this discussion the writer believes that the failure to obtain oil along the eastern margin of the Appalachian oil fields is due to the fact that here, because of the proximity of the outcrop of the oil sands (Figs. 4 and 5), the opportunity for water flushing was greater than in the central part of the synclinal basin. This explanation, the writer believes, is at any rate sounder theoretically and more fully in accord with the field data than the suggestion that heat and pressure eliminated the oil and gas or that the absence of these hydrocarbons is due to lack of pore space, as Russell suggests, because, as has been pointed out, deep wells drilled along the eastern margin of the field encounter flows of water and gas at depths of 5,000 to 7,000 feet. It also appears to the writer to be a more acceptable explanation than the one suggested by Tarr,[2] which attributes the absence of oil and gas to lack of source material, for in the Appalachian region the sediments in the oil fields do not differ materially from those east of the oil fields.

Occurrence of oil in formations where the carbon ratios exceed 70 per cent.—The claim that no commercial oil fields are found anywhere in or beneath formations in which the carbon ratios of the carbonaceous deposits exceed 70 per cent can scarcely be justified in view of the fact that oil is being obtained in the Appalachian and Mid-Continent fields at depths as great as 4,500 feet beneath surface coals that have carbon ratios of 55 to 60 per cent. The degree of alteration at such a depth is probably that of a coal with a carbon ratio of 70 to 80 per cent.

Supporters of the carbon-ratio theory may concede this and also acknowledge that there is no proof that degree of alteration of sediments, as indicated by carbon ratios of coals, has anything to do with the extent of our known oil and gas fields. They may insist, however, that irrespective of this lack of relationship, carbon ratios appear to offer a useful guide in the search for oil, because no commercial pools have yet been found where the carbon ratios of the surface coals exceed 70 per cent, and therefore that it is reasonable to assume that the chances for finding oil in such areas are not so good as in areas where the carbon ratios of the surface coals are less than 70 per cent. If the conditions

[1] J. L. Rich, "Moving Underground Water as a Primary Cause of the Migration and Accumulation of Oil and Gas," *Econ. Geol.*, Vol. 16 (1921), No. 6, pp. 360-63.

[2] R. S. Tarr, "Discussion of G. E. Dorsey's Paper, 'The Present Status of the Carbon Ratio Theory,'" *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 5 (May, 1927), pp. 463-65.

that prevail in the Appalachian fields were present in a number of fields, this claim would apparently be justified. But there are no other fields where the areal distribution of the oil and gas can be so closely correlated with the carbon ratio of the surface coals. An examination of the isocarb map of the Illinois fields (Fig. 1) shows no parallelism between isocarbs and the extent of the known fields. The same is essentially true for Croneis's map of the Mid-Continent field (Fig. 3), for the eastern margin of the field parallels no isocarb, and although there is no oil in the area where the carbon ratios are 70 per cent or more, oil is lacking also north of this area, where the carbon ratios are no higher than in the oil fields. In the fields of north-central Texas, also (Fig. 2), there are scarcely sufficient reliable data to draw a generalization as to the field relations between occurrence of oil and degree of alteration of surface coals.

Furthermore, the statement that there are no known oil fields in areas where the carbon ratios of the surface coals exceed 70 per cent loses its impressiveness when one realizes how small and few are such areas and to what a limited extent oil is found in the areas where the carbon ratios of the surface coals are less than 70 per cent. A rough estimate of the relative size of these areas for the North American continent has been undertaken. As far as possible, determinations of their magnitude were based upon published maps, and such allowances were made as the circumstances justified in order that the data might be presented as accurately as possible. According to the map published by Woodruff[1] showing the petroliferous provinces of North America, the areas underlain by sedimentary strata that contain source material and reservoir rocks favorable to the occurrence of oil aggregate about 2,750,000 square miles. In determining the percentage of this area in which the exposed rocks have reached a state of metamorphism comparable to that of a coal bed having a carbon ratio of 70 per cent or more, it is necessary to rely on coal reports. In the United States, according to Campbell's map,[2] semi-bituminous and higher-rank coals—that is, coals having a carbon ratio of 70 per cent or more—are found only in the Appalachian province, in the Arkansas River valley coal field, and in west-central Colorado, covering a total area of about 18,000 square miles. How much this area should be increased to include those areas within Woodruff's provinces where surface coals if present would have a carbon ratio of

[1] E. G. Woodruff, "Petroliferous Provinces," *Trans. Amer. Inst. Min. and Eng.* Vol. 65 (1921), Fig. 1, p. 202.

[2] M. R. Campbell, "Our Coal Supply; Its Quantity, Quality, and Distribution," *Proc. International Conference on Bituminous Coal*, 1924.

more than 70 per cent is a matter of conjecture, but the writer believes it is safe to assume that the total area would not be more than twice 18,000, or approximately 35,000 square miles. For the rest of the North American continent there are still fewer data from which to determine the areas where the surface rocks have reached this stage of alteration. But in view of the fact that the United States constitutes nearly one-half of the total area and contains more than half of the petroliferous provinces, it will be assumed that in the petroliferous provinces of the North American continent the area in which the surface rocks have attained a degree of metamorphism equal to, or more than, that represented by a carbon ratio of 70 per cent is 70,000 square miles, and that in the rest of the petroliferous provinces, or in 97 per cent of the whole, the metamorphism of the surface rocks is less than this. Of the total area, however, 50,000 square miles, or less than 2 per cent, yields oil.[1] Considering, therefore, that the areas producing oil and those in which the surface rocks have attained a stage of alteration comparable with that of a coal having a carbon ratio exceeding 70 per cent cover less than 2 per cent and 3 per cent, respectively, of the petroliferous provinces, the fact that they have not yet been found to overlap does not seem to justify the assumption that they will not sometime be found to overlap.

Moreover, the writer believes that in the light of our present knowledge of the occurrence of oil in the North American continent, it is not justifiable to claim that oil is not found where the degree of metamorphism of the surface rocks exceeds the stage represented by a carbon ratio of 70 per cent. For example, in the Canadian Front Range in southwestern Alberta small oil wells have been obtained and numerous oil seeps are known in a structural province in which the Kootenai coals, 35 miles farther north, are semi-anthracites. Again, it may be pointed out that the Katalla oil field, in Alaska, lies but 15 or 20 miles south of the Bering coal field, in which the carbon ratio of the surface coals ranges from 80 to 84 per cent.[2] Coal has not yet been found in the oil field, but the geologic conditions are so similar in the two areas that there is justification for assuming that the degree of alteration of the sediments is the same for both.

[1]In arriving at this estimate all areas of 36 square miles in which one or more commercial oil wells have been obtained are included. The area of actual production s much less than this.

[2]This field is cited by White as a possible exception to the generalization that no commercial oil fields are found where the carbon ratios of the coals exceed 70 per cent.

CONCLUSIONS

Although the idea of correlating degree of metamorphism with occurrence of oil and gas appears plausible because of the fact that in the metamorphic process the rocks become increasingly less porous and less capable of yielding oil and gas, there seems to be no theoretical or observational basis for the claim that, in the incipient stages, wherein the coals have scarcely reached the semi-bituminous rank, the oil and gas are eliminated. Any attempt to correlate occurrence of oil and gas with degree of metamorphism in its more advanced stages must take into consideration the fact that the chief variation in the degree of metamorphism is in the vertical direction, and therefore that the occurrence of the oil and gas in any sand must be compared with the degree of alteration of that sand and not with that of a coal that may occupy a position much higher in the stratigraphic series. This line of investigation, however, the writer believes does not appear to offer any promise of yielding results that would be useful in the search for new oil fields.

ACKNOWLEDGMENTS

In compiling the data embodied in this paper the writer was assisted by many of his colleagues in the United States Geological Survey, to whom he wishes here to express his thanks. He is especially indebted to W. W. Rubey and A. C. Spencer for the aid they gave him in interpreting these data.

RELATIONSHIP BETWEEN OVER- AND UNDER-THRUSTING AS REVEALED BY EXPERIMENTS[1]

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ABSTRACT

The results of the well known and oft-repeated experiments in which building stone is subjected to pressure are believed to be the key to an understanding of structural conditions in orogenies which are sufficiently exposed to be studied as a unit. These principles also appear to be applicable to rotational pressure, and give valuable information regarding the relationship between over- and under-thrusting. Numerous experiments seem to indicate that both over- and under-thrust faults, as well as over- and under-folds, develop during growth of orogenic units, be they large or small. The ratio between over- and under-thrusting, as revealed in the experiments performed, was approximately 2 to 1.

Surficial compression gave rise to closely folded uplifts with low-angle overthrusts and high-angle underthrusts, while deep-seated compression resulted in broad dome-or plateau-like uplifts, bounded by high-angle upthrusts and faint low-angle underthrusts. Applications of these ideas are made to several orogenic units.

INTRODUCTION AND ACKNOWLEDGMENTS

The conclusions presented in this paper are based upon some of the fifty experiments performed in the geophysical laboratories at the University of Chicago as partial fulfillment of the requirements for the degree of doctor of philosophy.[3] The writer is indebted to Professor R. T. Chamberlin of that University for aid in arriving at deductions from the experiments and to A. J. Seymour of Rosenwald Hall for help in preparing and performing them. Due to limited space in this *Bulletin* no description of apparatus and detailed account of the artificial sediments prepared is given here. Much of this information accompanies the diagrams and photographs of the experiments.

[1]Read before the Association at the San Francisco meeting, March 22, 1928. Manuscript received by the editor, April 12, 1928.

[2]Imperial Oil, Ltd., 239 Sixth Avenue West.

[3]Previous articles based on others of these experiments have been published as follows:

R. T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. of Geol.*, Vol. 35 (1927), No. 4, pp. 319-52. Theodore A. Link, "The Origin and Significance of 'Epi-Anticlinal' Faults as Revealed by Experiments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), No. 8, pp. 853-66.

PROBLEM

The use of the terms *over-* and *under-*thrusts when applied to mountain systems or individual structures necessarily implies an assumption on the part of the observer. The direction of operative forces or stresses[1] is assumed. Since the direction and manner of the application of force is known in structures produced experimentally, the use of these terms when applied to the experiments in question is permissible and implies no assumption. The object of the writer is to point out some relationships between over- and under-thrusting as revealed by experiments, and to attempt an application of the principles derived in the laboratory to orogenies which are sufficiently exposed to be studied as a unit.

INITIAL BREAK AND ULTIMATE FAULT PLANE

Before attempting a discussion on the theoretical and actual results of these experiments it is in place to make a few preliminary statements so as to avoid ambiguity. Many fault planes as they are observed in the field do not show the dip of the fracture plane at which they originally broke. Fault planes like the Lewis and the Bannock overthrusts certainly did not originally break at such extremely low angles. The angle at which the initial break took place is generally higher than the plane on which competent massive beds are pushed over the more incompetent members. The angle of the initial break, which invariably occurs in the more brittle strata of a given section, is ordinarily higher than the gliding plane and, unfortunately, in many places is hidden from view. Furthermore, many of the low-angle shear planes are deflected toward the surface at higher angles. Examples of these are discussed under a separate heading. All fault or shear planes referred to in the following discussions are regarded as the *initial* break unless specified to the contrary.

BASIC ELEMENTARY PRINCIPLES

Cubes of building stone or similar relatively homogeneous material, when subjected to non-rotational pressure, have a tendency to fracture or break along planes at angles close to 45 degrees to the principal axis of stress. The ordinary manner of fracturing is pictured in cross section in Figure 1. If considered as a solid, the cube is divided by the resulting fracture planes into six equal pyramids the apices of which all point toward the center *B*. Two of these pyramids, *ABD*

[1]The term "stress" is here used in the geological sense as defined by Leith, namely, "The *force* tending to deform a rock is often spoken of as a *stress*." C. K. Leith, *Structural Geology* (Revised Edition), Henry Holt & Co., p. 15.

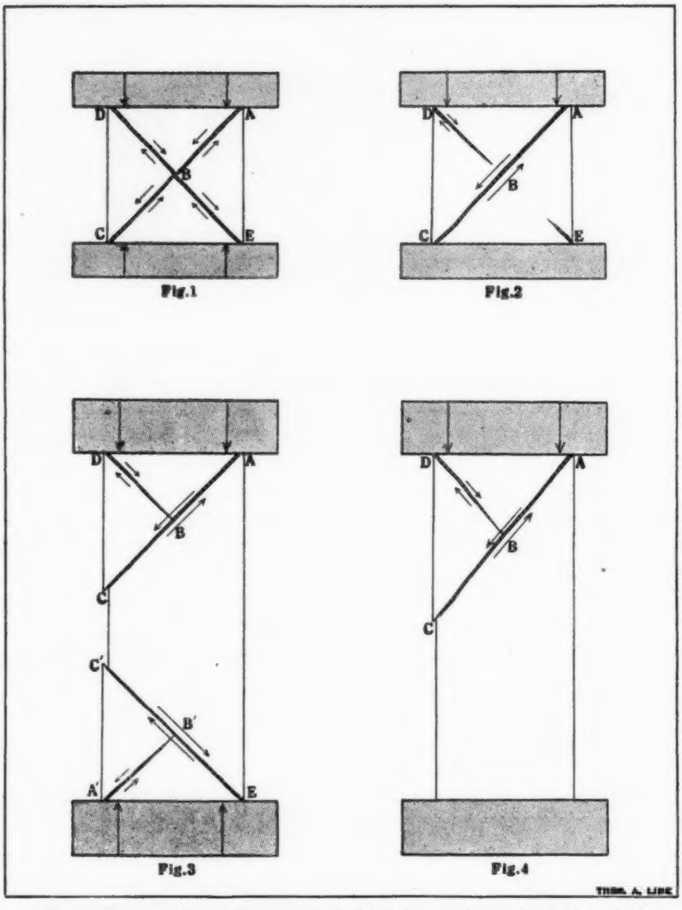

FIG. 1.—Cross section of homogeneous cube deformed by uniformly applied compressive force acting from top and bottom. Fracture (initial break) planes *ABC* and *DBE* develop at an angle slightly lower than 45 degrees to the principal axis of stress. Arrows indicate relative shearing movements.

FIG. 2.—Cross section of cube deformed by compressive force from above. *ABC* is the major shear plane. *DB* and *EB* are incipient arrested fracture planes.

FIG. 3.—Cross section of a prism deformed by compression from opposite ends. *ABC* and *EB'C'* are major shear planes, *DB* and *A'B'* are arrested fracture planes.

FIG. 4.—Cross section of a prism deformed by compression from one end, giving rise to major shear plane *ABC* and fracture plane *DB*. Compare this with Figure 5.

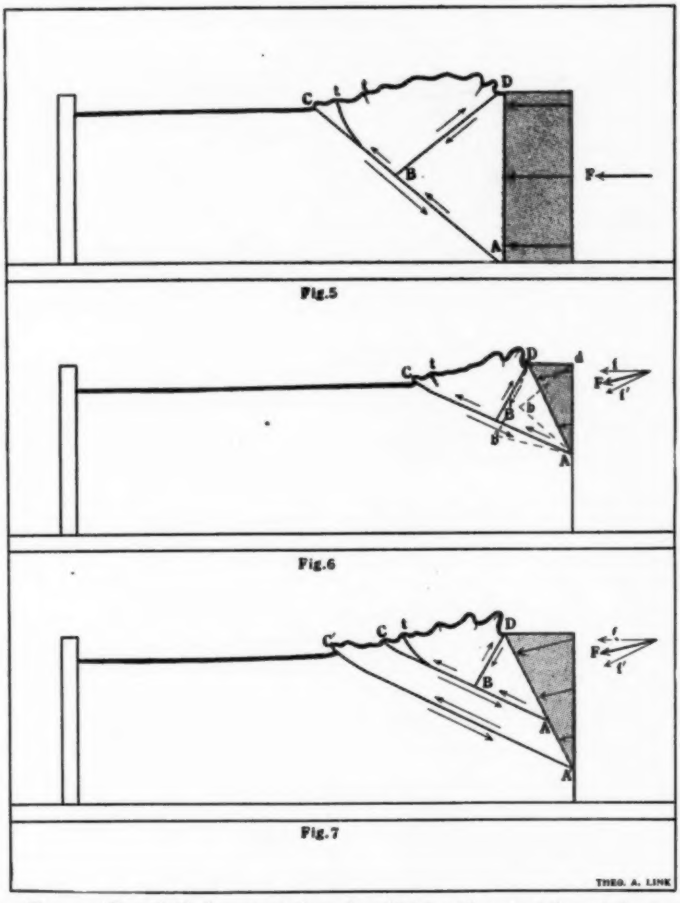

FIG. 5.—Hypothetical cross section of artificial sediments deformed by non-rotational compression. *F* indicates direction of pressure application; *AD*, face of push-block; *ABD*, cone of shear; *DBC*, wedge; *ABC*, overthrust fault plane; *DB*, underthrust fault plane. Arrows indicate relative displacements along shear planes. Strike tension fissures, marked *t*, deflect low-angle thrust faults toward the surface at high angles.

FIG. 6.—Cross section of artificial sediments deformed by rotational compression. Face of push-block *AD* pushed into sediments by force *f* which tends to develop cone of shear *Abd*. Force *f'* (right angles to face) tends to develop cone *Ab'd*. Actual force operative is resultant *F* which develops cone *ABD* and wedge *DBC*. Other symbols same as Figure 5.

FIG. 7.—Same as Figure 6 after more compression. Shear plane *ABC* hinders downward extension of underthrust *DB*, thus causing dominant development of overthrust faults.

and *CBE* have their bases against the push-blocks and are forced against each other, apex to apex, while the other four pyramids move outwardly away from *B*, as indicated by the arrows.[1] Spheres of relatively homogeneous material respond to simple compression in essentially the same manner. Figure 11 illustrates a sphere which developed two perfect "cones of shear," apex to apex, and three outwardly moving segments. A cross section through this deformed sphere is illustrated in Figure 12. For simplicity the pyramid *ABD*, which has its counterpart in this cone, will hereafter be referred to as the "cone of shear" or merely "the cone." The outwardly moving segments will be termed the "wedges" since such is their shape when observed in cross section.

The condition pictured in Figure 1 is the ordinary manner of initial fracture when uniform compression is applied to a cube of homogeneous material. If pressure is applied from one side only, fracturing as illustrated in Figure 2 very commonly results. In this case the shear plane *ABC* becomes the master plane while the other planes and the cone of shear *ABD* are only imperfectly developed. If the cube were turned over on its right side, *AE*, this would make the plane *ABC* an overthrust fault.

Figure 3 illustrates what ordinarily takes place when pressure is applied to a mass with enough length to preclude the cones of shear from meeting tip to tip. Here again it is clear that *ABC* is an overthrust and *DB* is an underthrust shear plane.

Figure 4 illustrates a common method of fracture when a mass of considerable length is subjected to compression from one end only. Almost invariably one of the shear planes (in this case *ABC*) develops as the major plane, and almost all displacement results along this plane. If the mass being deformed is not homogeneous throughout, or if pressure is not applied uniformly, the tendency to fracture and slip along one major plane rather than four is greatly enhanced. Also by supporting one side, or two, or three sides it is possible actually to force the development of the major shear plane in one direction. To be specific, this is exactly what is done in using the ordinary laboratory apparatus. A mass to be deformed by application of pressure is confined in a pressure box open on one side only, the top. Relief of stresses is, consequently, primarily *upward*. The major shear plane developed under such conditions is the overthrust fault *ABC*. As discussed previously,[2] there is also a lateral relief of stresses, but maximum relief in all cases is *upward*.

[1]C. K. Leith, *Structural Geology* (Revised Edition), Henry Holt & Co., New York, p. 35, Fig. 11, in which is illustrated fracture of building stones.

[2]Theodore A. Link, "The Origin and Significance of 'Epi-Anticlinal' Faults as Revealed by Experiments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 8 (August, 1927), p. 853.

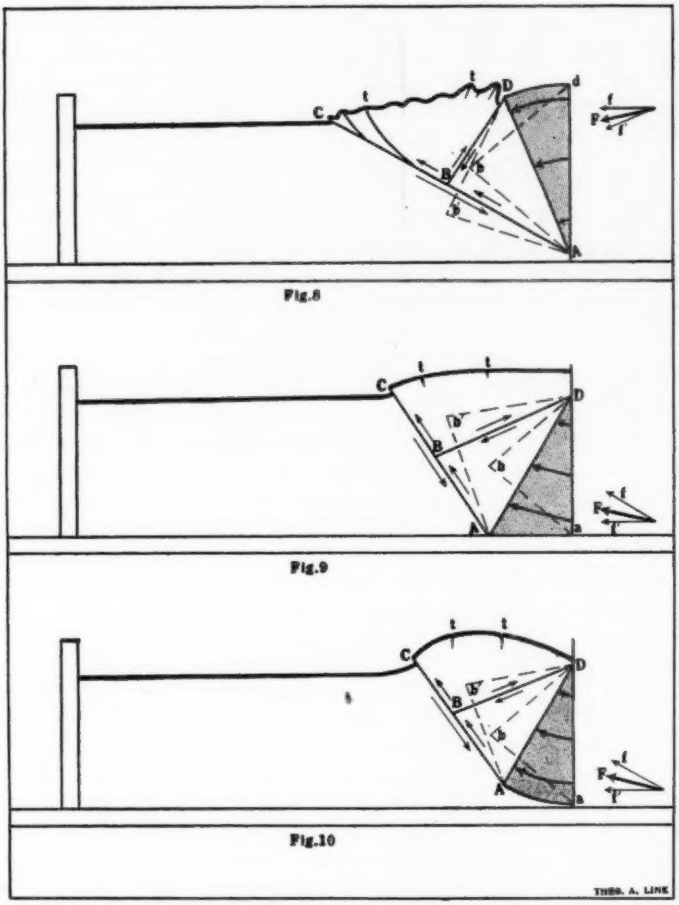

FIG. 8.—Hypothetical cross section of artificial sediments subjected to rotational compression. Push-blocks held by hinge at A and rotated against the strata. Force f, acting in horizontal direction, tends to develop cone of shear Abd. Force f' (face of push-block) tends to develop cone $Ab'D$. Force F, the resultant of f and f', develops cone of shear ABD, and the wedge DBC bounded by low-angle overthrust ABC and high-angle underthrust DB. Tension fissures t deflect low-angle thrust planes toward the surface at steep angles.

FIG. 9.—Cross section of artificial sediments subjected to deep-seated rotational compression. Force f' should tend to develop cone of shear abD. Force f tends to develop cone $Ab'D$, but actual force F (resultant of f and f') develops cone of shear ABD and wedge DBC bounded by upthrust ABC and low-angle underthrust DB. Tension fissures, marked t, develop on plateau-like uplift.

FIG. 10.—Same as Figure 9 but push-block held by hinge at D and rotated against sediments. This gives rise to broad dome-like uplift with strike tension fissures t, etc.

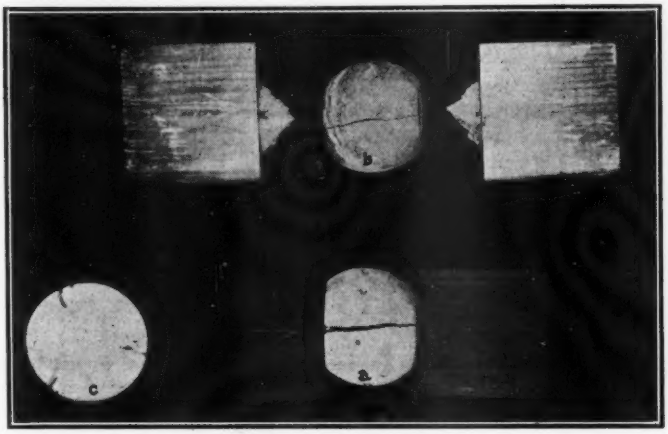

FIG. 11.—Deformation of spheres of plaster of Paris: *a*, sphere deformed by compression from the left (notice the tension fissure); *b*, same as *a* after pulling apart the push-blocks (notice the cones of shear developed at an angle near 45 degrees to the principal axis of stress); *c*, end view of deformed sphere illustrating the development of tension fissures at intervals of 180 degrees.

NON-ROTATIONAL STRESSES

Experiments have demonstrated the principles previously cited. By observing the various steps of an experiment through heavy plate glass sides, it was possible to get a good idea of the manner and sequence of fracturing in the deformed artificial strata. The order of events as observed in several experiments is somewhat as pictured in Figures 13 to 16 and described as follows.

1. Upon application of pressure the first thing noticeable is a compacting of the material directly in front of the push-block in the area of the cone *ABD*. This is generally manifested by a squeezing or "sweating out" of the included water in this compacted triangle or cone (Fig. 13).

2. Incipient bulging at the surface between *D* and *C*, and slight wrinkling near *D* is next observable.

3. Incipient overthrust faulting along and near plane *AB* with further bulging and wrinkling at the surface and slight compacting within the wedge *DBC* (Figs. 14 and 17).

4. Slight underthrusting along or near plane *DB* with continued compacting, uplift, and folding at the surface and in the wedge *DBC* (Fig. 14).

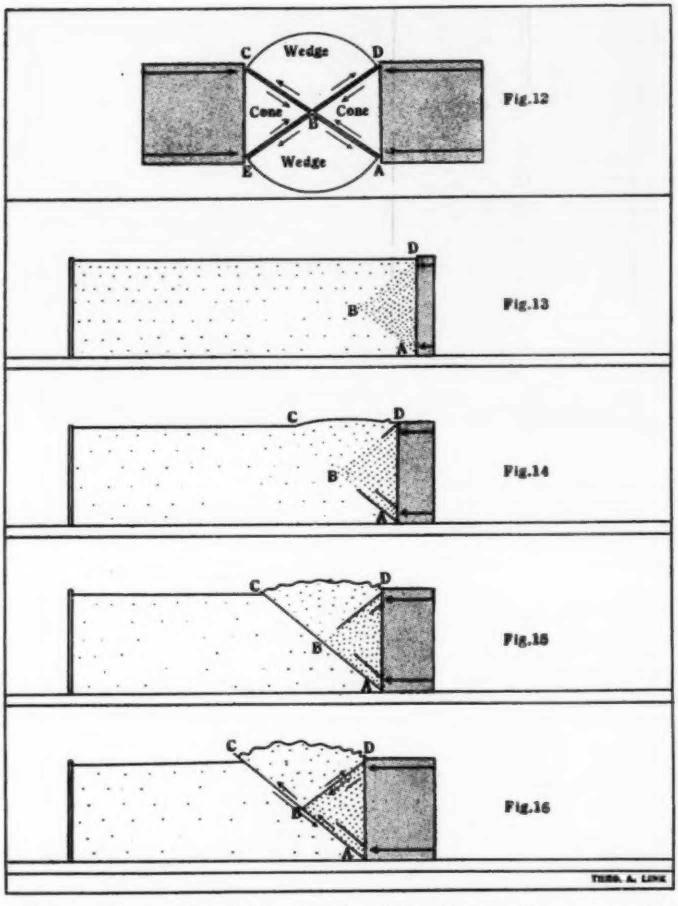

FIG. 12.—Cross section of deformed sphere illustrating use of terms *cone of shear* and *wedge*.

FIG. 13.—Soon after application of pressure the first noticeable change is a compacting of the material in front of the push-block in the area of the cone *ABD*.

FIG. 14.—Incipient bulging at the surface between *D* and *C*, slight wrinkling near *D*, incipient faulting in lower portion of cone and also in upper part near *D*. Continued compacting in the wedge area *BDC*.

FIG. 15.—Extension of overthrust shear plane *ABC* to the surface, and underthrust plane toward *B*. Continued deformation within the wedge and cone.

FIG. 16.—Growth of underthrust fault until reaching *B*, uplift of wedge *DBC* causing displacements along over- and under-thrust fault planes as indicated by the arrows.

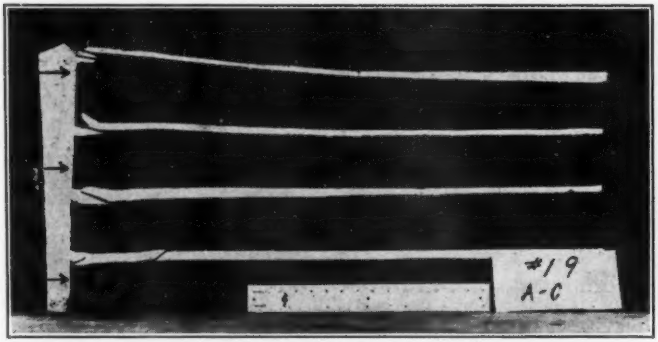

FIG. 17.—Experiment which was halted after very slight compression, illustrating the initial overthrust breaks at depth and underthrusts higher up. An incipient cone of shear. White layers are plaster of Paris. Dark layers, sand mixed with cement.

5. Overthrusting along or near plane *ABC* becoming stronger and finally reaching the surface at or near *C* (Fig. 15).

6. Underthrusting becoming more pronounced along *DB* but its downward extension being checked at *B* by the previously developed overthrust plane *ABC* (Fig. 15).

7. Further application of pressure causes wedge *DBC* to be forced upward, thus increasing displacements along the over- and underthrust fault planes bounding the wedge (Fig. 16).

8. Extreme compression will obliterate the framework of the wedge and cone here outlined, and may repeat the process in the relatively undisturbed portion in front of the compacted and faulted sediments.

Two experiments (Figs. 18 and 19) illustrate strikingly the pronounced development of the cone of shear and the wedge. These particular experiments were performed in an apparatus fitted with a strong plate glass side, and the sequence of events was actually observed. Similarity of behavior in the two experiments is significant when the fact is considered that different kinds of material were used for the two experiments. In one, plaster of Paris layers were alternated with plaster-cemented sand, and in the other, layers of grease (petrolatum) were alternated with plaster-cemented sand.

In considering the order of events as outlined, it is important to understand that the nicety of results as developed in Experiments 35 and 36 (Figs. 18 and 19), is not exhibited under all conditions and may be obliterated by too prolonged application of pressure. The develop-

ment of the underthrust element may be almost wanting and the overthrusts predominate. This is, in many cases, due to an excessive overburden, as will be pointed out later. However, there is the ever-present *tendency* toward the development of a cone of shear and its complement,

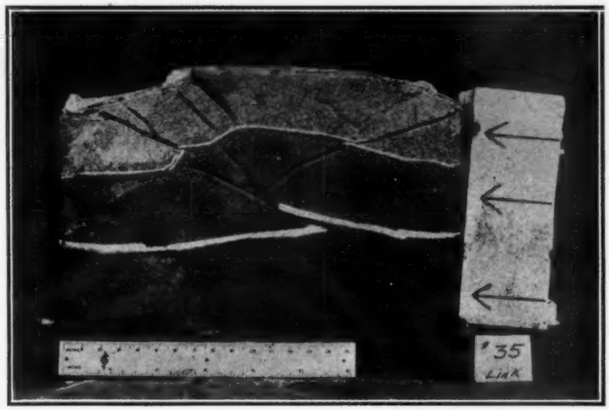

FIG. 18.—Illustrating experiment 35, which was observed through a double plate-glass side. Notice the cone of shear, its complement, the wedge, bounded by an over- and under-thrust fault, and branching thrust faults deflected toward the surface at higher angles. Same sort of sediments as in previous figure.

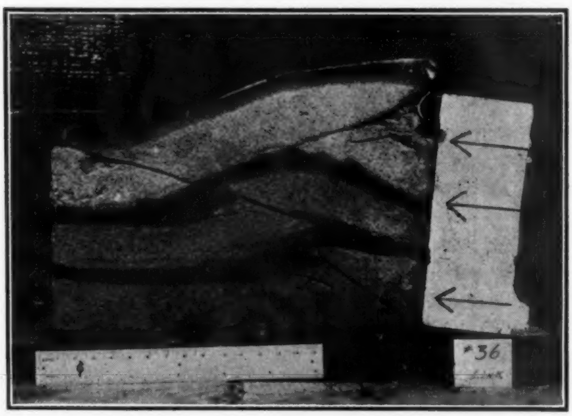

FIG. 19.—Illustrating results similar to those in experiment 35. Notice that here layers of grease instead of plaster of Paris were employed.

the wedge, just as there is when deforming homogeneous building stone by simple compression. The presence of alternating hard or soft, brittle, or more or less elastic layers necessarily complicates matters by changing the initial break or faults to higher or lower angles, thus tending to obliterate the cone and wedge relationship. Strike tension fissures are also important factors in deflecting faults. They will be discussed under a special heading.

In conclusion, it can be stated that *non-rotational compression has a tendency to develop initial shear planes at angles slightly less than 45 degrees to the principal axis of stress, giving rise to the cone of shear and a symmetrical wedge bounded by overthrust and underthrust fault planes dipping at about a 45-degree angle to the surface.*

ROTATIONAL STRESSES

A. MAXIMUM COMPRESSION AT SURFACE

Experiments were performed in which push-blocks were forced into the artificial sediments in such a manner as to effect a maximum shortening or compression at the surface and none at depth. The method of pressure application is illustrated in cross section in Figures 6 to 8. Applying compression in this manner always resulted in surficial tightly folded structures, low-angle overthrusts, and high-angle underthrusts and underfolds. The results of these experiments seemingly indicate that the cone-of-shear and wedge conception is also applicable in a manner somewhat as shown in the following paragraphs.

By applying a push-block as indicated in Figure 6, two forces are put in operation. One force, f, acts horizontally from right to left, while another force, f', acts at right angles to the face of the push-block AD. The resultant of these two forces would be F. The force f tends to develop the cone of shear Abd while force f' should develop cone $Ab'D$. The resultant force F should give rise to a cone intermediate between the two just mentioned, namely, cone of shear ABD. Thus there arises a wedge DBC which is bounded by low-angle overthrust and high-angle underthrust faults. Further application of pressure (Fig. 7) would give rise to more low-angle overthrusts at depth $A'C'$, but the underthrusts would not extend to a very great depth because of the previously developed overthrust ABC arresting their downward extension. This development is based on the assumption that the push-block is not forced into the sediments with a rotary movement, but by horizontal movement from right to left so that the face of the push-block maintains the same angle with respect to the artificial sediment.

If the push-block is held by a hinge at A, as shown in Figure 8, and rotated against the sediments, very similar results are obtained. At the outset of pressure application the cone of shear Abd would develop if the maximum compacting were to take place at once. If the maximum compacting were to take place after the push-block had been rotated to AD then the cone of shear $Ab'D$ would result. However, the limit of compacting is generally reached at some intermediate stage; thus the cone ABD results, due to the force F, the resultant of f and f'.

This analysis is best condensed into the statement that *under rotational compression the principal axis of stress changes its attitude with respect to the surface; consequently, underthrust and overthrust shear planes, which bound the cone of shear and the resulting wedge, change their attitude with respect to the surface, but maintain the same angle with respect to the principal axis of stress.*

Maximum surficial compression, as effected in these experiments, gave rise to asymmetrical wedges bounded by initial low-angle overthrust fault planes as well as closely folded or plicated surficial over- and under-folds dying out rapidly at depth. Examples of these are illustrated

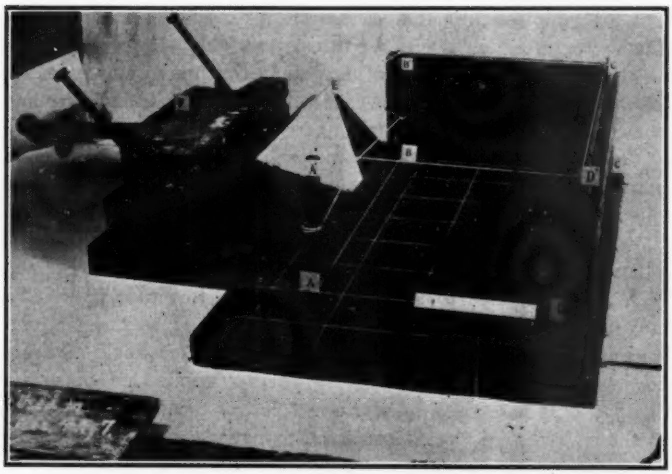

FIG. 20.—Illustrating the apparatus and method of applying surficial compression dying out laterally and at depth which gave rise to closely folded arcuate uplift. Position of buffer before application of pressure. Movable buffer E is held by a hinge at its base and is forced against the side AA'-BB' which is composed of a flexible fiber-rubber sheet so as to adjust itself to the shape of the buffer. Squares represent 10 centimeters. Sides partially removed to reveal buffer.

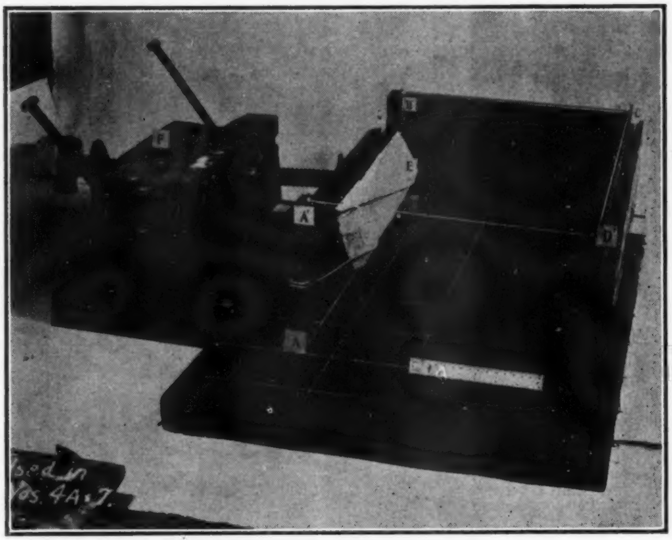

FIG. 21.—Same as Figure 20 *after* application of pressure.

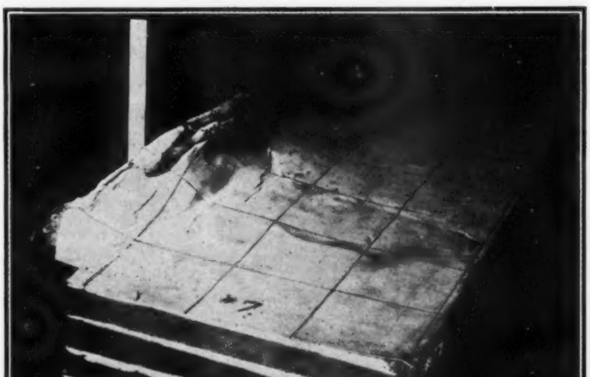

FIG. 22.—Stereogram view of model produced by applying pressure as described in Figures 20 and 21. Notice the closely folded and arcuate nature of the uplifts. Squares represent 10 centimeters. Layers of plaster of Paris interbedded with cement-indurated sand. (Experiment 7.)

and explained in Figures 21 to 26. Attention is here again called to the distinction between *initial* break and the *ultimate* fault or shear planes. A fault plane which breaks at a given angle may not continue at that angle, as already pointed out; in consequence, the original shape or angle relationship of a wedge or cone of shear may be slightly or entirely obliterated by extreme application of pressure. Another important factor is the development of strike tension fissures. These will be discussed under a separate heading.

FIG. 23.—Ground plan or top view of experiment 7 after removal of blotting paper from all but the tightly folded part. Notice in particular the arcuate shape of the uplift and the transverse tension fissures or flaws converging toward the locus of maximum compression. *AB* and *A''D* indicate position of cross sections illustrated in the following two figures.

B. MAXIMUM COMPRESSION AT DEPTH

Figures 9 and 10 are cross sections representing a geometrical analysis of deep-seated compression or shortening diminishing upward toward the surface as effected in the experiments. The push-block was forced against the artificial sediments at an angle, as shown in Figure 9.

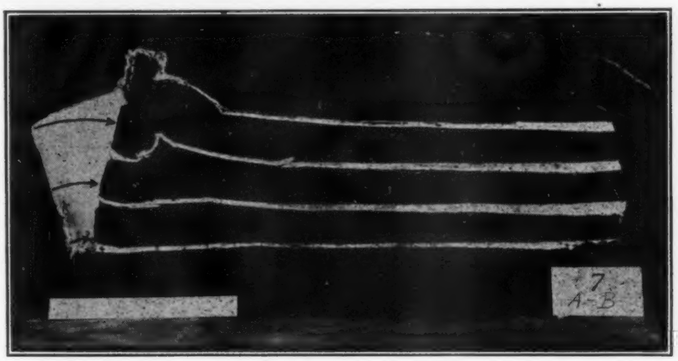

FIG. 24.—Cross section *AB* cut through experiment 7 illustrated in the previous figures. Notice the low-angle overthrust tendency at depth and the underthrust and underfold tendency higher. Scale represents 15 centimeters.

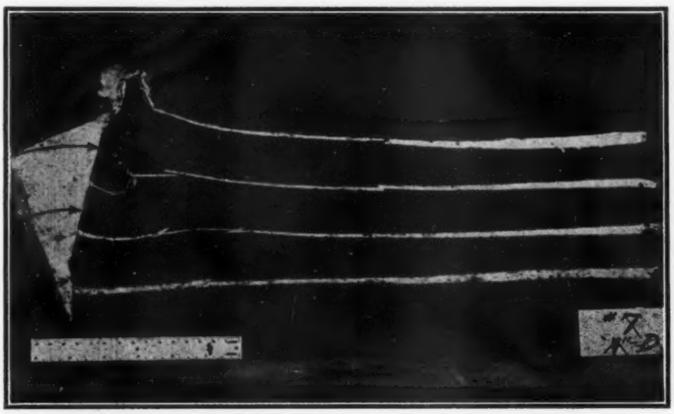

FIG. 25.—Cross section *A″D* cut through experiment 7 illustrating low-angle overthrusts at depth, compared with underfolds and underthrusts higher. Cone of shear not completely developed.

FIG. 26.—Illustrating surficial compression as observed through heavy plate-glass side. Notice the low-angle overthrusts and high-angle underthrust fractures and surficial underfolds. Dark layers are grease. Lighter layers, cement-indurated sand.

Here again a horizontal force, f', acting from right to left, and force f acting at right angles to the face of the push-block were brought into play. Force f' would tend to develop the cone of shear *abD*, while f would cause the formation of cone *Ab'D*. The resultant of these two forces, *F*, which is the actual active force, would develop the cone of shear *ABD*, and if carried far enough would give rise to the high-angle upthrust *ABC*, and the low-angle underthrust *DB*, bounding a broad plateau-like uplift or wedge.

If the push-block is held by a hinge at *D* and rotated against the artificial sediments as shown in Figures 10, 27 and 28, the results are very similar except that in this case the uplifted wedge is a broad, dome-like feature bounded by a high-angle upthrust and possibly a low-angle underthrust. In both these cases the underthrust element is only slightly developed and, as a rule, confined to the lower parts of the wedge. Experiments illustrating these phenomena are pictured in Figures 29 to 32.

Extreme rotation of the push-block against the sediments, as shown in Figure 10, would give rise to upthrusts turned back on themselves. These could very well be described as "discoidal faults" and their counterpart in nature would be associated with deep-seated movements with forces acting almost vertically, like a batholithic mass forcing its way toward the surface.

DEFLECTION OF THRUST FAULTS BY TENSION FISSURES

Along the crests of anticlines and along trough lines of synclines, where the maximum amount of stretching takes place, longitudinal ten-

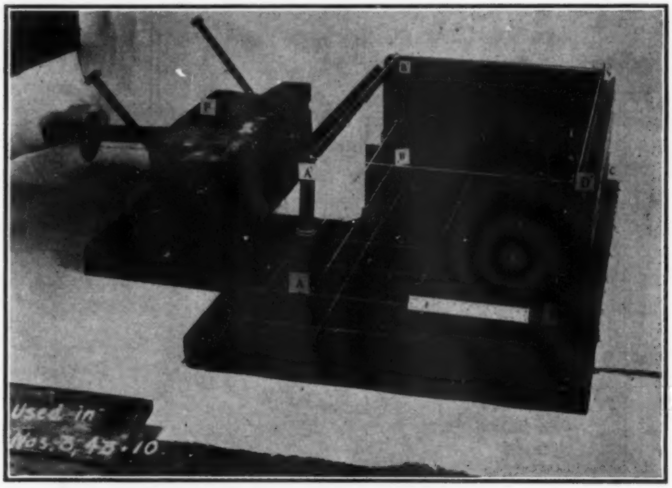

FIG. 27.—Illustrating the apparatus and method of applying pressure giving rise to "turtle-back" domes. Movable buffer E is held by a hinge at the top, and is forced against the side AA'-BB' which is composed of a flexible fiber-rubber sheet so as to adjust itself to the shape of the buffer. Position *before* application of pressure. Squares represent 10 centimeters. Sides partially removed to reveal buffer.

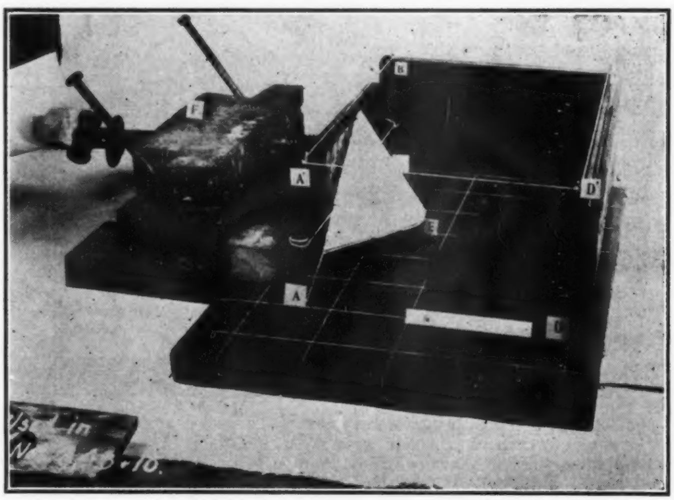

FIG. 28—Same as Figure 27 *after* application of pressure.

sion fissures are commonly developed. Many tension fissures (marked "*t*" in Figures 5 to 10) deflect low-angle overthrust faults toward the surface at extremely high angles. This principle was recognized by

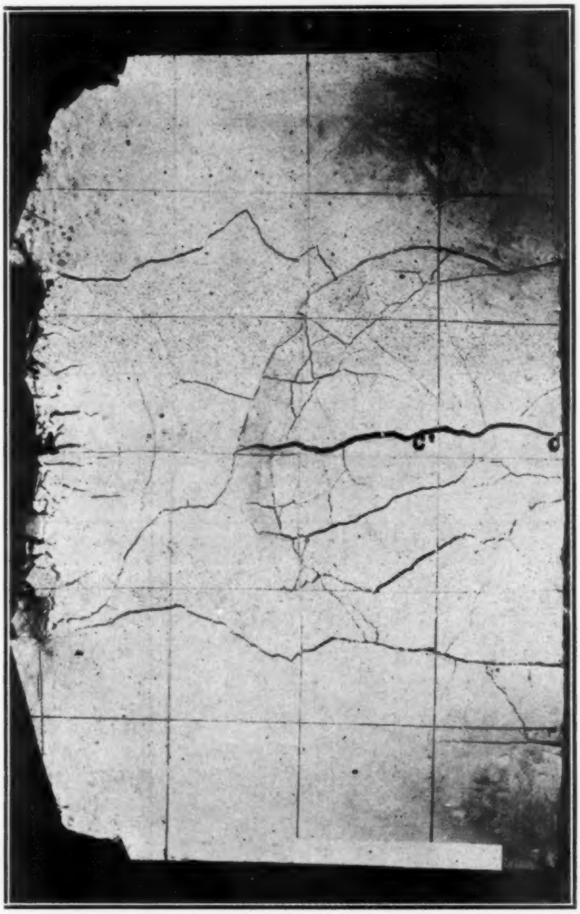

FIG. 29.—Ground plan or top view of experiment 4. On right side is a plateau-like uplift produced by deep-seated compression and on left side is a closely folded narrow, arcuate uplift produced by surficial compression. Notice tension fissures converging toward loci of maximum compression. *A'C'C* indicates position of cross section illustrated in Figure 30. Squares represent 10 centimeters.

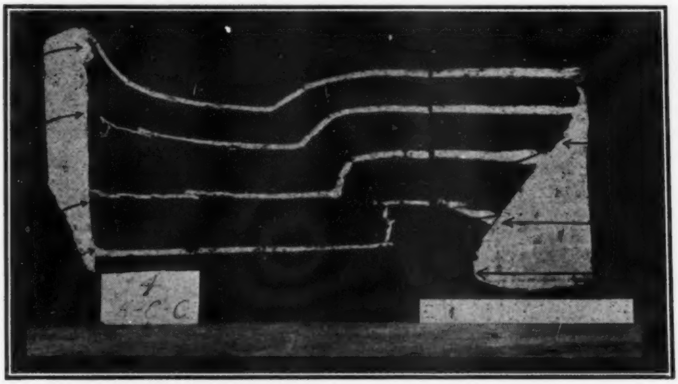

FIG. 30.—Cross section *A'C'C* cut through experiment 4 illustrating deep-seated compression giving rise to plateau-like uplift on the right, and surficial compression causing tightly folded uplift on the left. Break through the plateau is due to cut made by the saw parallel to the strike of the uplift. Scale represents 15 centimeters. Notice the high-angle upthrust tendency and the low-angle underthrusts at depth in the plateau structure.

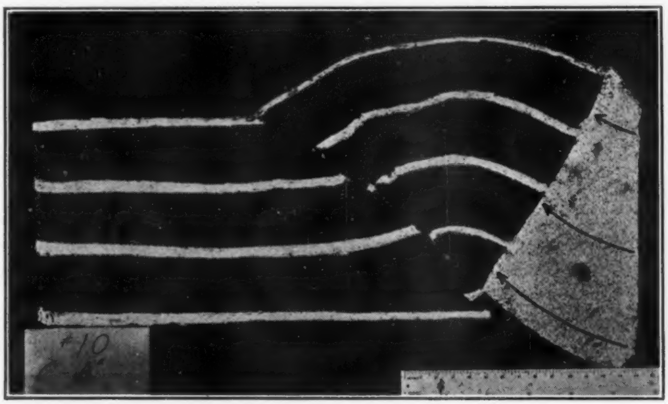

FIG. 31.—Illustrating a cross section cut through model of experiment 10 in which deep-seated compression was effected by rotating push-block held by hinge at top and as indicated by the arrows. Broad dome-like uplift bounded by a high-angle upthrust. No underthrusts developed here.

Bailey Willis[1] in the report on his classic experiments, and also by other experimenters, especially T. T. Quirke,[2] who placed much stress on it.

[1]Bailey Willis, "The Mechanics of Appalachian Structure," *U. S. Geol. Survey, 13th Ann. Rept.*, Part 2 (1893).

[2]T. T. Quirke, "Concerning the Process of Thrust Faulting," *Jour. of Geol.*, Vol. 28 (1920), pp. 417-38.

FIG. 32.—Deep-seated compression as observed through a plate-glass side. Push-block was rotated against strata as indicated by arrows. Notice the high-angle overthrust, and the fault "grabens" developed on top of the dome-like uplift.

It is apparent that such a deflection of low-angle overthrust faults can give rise to misleading interpretations regarding the nature of the forces which caused them. In the opinion of the writer the high-angle thrust faults exposed in the Foothills belt of Alberta, Canada, are deeper-lying low-angle overthrust faults deflected toward the surface by strike tension fissures. As already stated, low-angle overthrust faults are to be associated with surficial stresses provided they accompany tightly folded structures. If, however, such faults are deflected at high angles toward the surface care must be taken not to confuse them with the initial high-angle upthrusts which accompany deep-seated stresses. The association of tightly folded structures with high-angle overthrusts is sufficient information to prevent such a misinterpretation. This branching of a thrust fault into smaller thrust planes was recognized by Cadell[1] in his experimental studies.

In extreme cases a tension fissure, dipping at a very high angle in a direction opposite to that of a growing low-angle overthrust fault, might actually deflect the latter in such a manner as to give rise to an overthrust turned back on itself. Such a result would be similar to the "discoidal" fault alluded to under deep-seated upthrusts. Here again this fault should not be confused with the initial fault developed by deep-seated stresses because of its association with tightly folded structures. The

[1]H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh 35* (1890), pp. 337-57.

development of such a fault is illustrated in Figure 33. The writer suggests the term "pseudo-discoidal" fault for this type.

If nothing were known regarding the nature of such a fault it would be mapped correctly as a normal fault since the hanging wall is on the downthrown side. It is the opinion of the writer that many of the very high-angle faults heretofore mapped as normal faults are nothing other than thrust faults deflected at high angles near the surface, and in consequence thrust faults are probably far more numerous than has heretofore been recognized.

The writer and others have encountered *seemingly* normal faults along the crests of tightly squeezed anticlinal structures, some of which are isoclinal. Such folds indicate beyond doubt that tangential compression was the major operative factor, while the undeniable demonstration of normal faulting, exhibiting, in many places, planes dipping away from the assumed direction of active compression, makes this structure seem utterly at variance with all principles of mechanics. It is therefore suggested that such seemingly normal faults are "pseudo-discoidal" and, at depth, may be continuous with low-angle overthrusts dipping in the opposite direction.

IMPORTANCE OF UNDERTHRUSTING

Although the conception of *underthrust* is not a recent one in structural geology there is still a reluctance on the part of some students to include it in the same class as that of overthrusts. In 1914 W. H. Hobbs[1] urged the importance of underthrust faults and actually attempted to demonstrate that their development is more common than that of overthrust faults. Again, at the meeting of the Geological Society of America at Madison, Wisconsin, December, 1926, A. C. Lawson presented in his presidential address a theory assigning the formation of the Lewis thrust fault of Montana and southern Alberta to underthrusting acting *from east to west.* The conception seems, therefore, to be gaining favor, and inquiry into the data regarding it, as revealed during the course of the experiments here described, seems fitting at this point. Without repeating the mechanics of the development of underthrusts it is well to summarize the frequency of their development as revealed in thirty-two experiments on tangential compression performed by the writer. The important, or rather, all the undeniable over- and under-thrusts exhibited in the observed cross sections were tabulated in the following manner.

[1] W. H. Hobbs, "The Mechanics of the Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. 22 (1914), pp. 166-81.

All thrust faults showing a displacement in cross section were counted. If a fault cut one layer it was recorded as one fault, and if it cut two distinct layers it received the value of two. Also, the same faults encountered in one cross section were again counted as distinct faults in another cross section of the same model. Mere breaks showing no displacement were ignored while complicated over- or under-thrust folds were regarded as only one fault. The over- and under-thrust faults occurring in pairs so as to form small inverted and upright wedges were also tabulated and their development is discussed under a separate heading. The following are the statistics for all the experiments.

SUMMARY OF RELATIVE FREQUENCY OF OVER- AND UNDER-THRUST FAULTS

Experiment No.	*Overthrust Faults*	*Underthrust Faults*	*Distinct Pairs of Faults, or Small Wedges*
1	3	5	3
2	16	3	1
3	21	3	0
4A* & B*	14	17	2
7	5	10	1
9A, B*, and C	13	7	3
10*	15	0	0
13	6	11	0
15	9	9	2
17	19	16	2
19	8	12	3
20	28	30	2
23	64	5	0
27	0	3	0
29	0	2	0
34	5	5	0
35*	7	3	0
36*	4	2	0
37*	3	0	0
38*	4	3	0
39*	4	5	0
40	4	1	0
41	2	1	0
44	2	0	0
45	2	1	1
46	2	1	1
47	2	2	2
48	3	0	0
49	2	1	0
50	7	6	0
Grand total	284	164	23

*Illustrated in part in this paper.

The method employed in counting the faults tended to favor the overthrusts because, as already pointed out on pages 833 and 834, all the underthrusts are shorter than the overthrusts. (See Figures 1 to 10.) In consequence the latter ordinarily cut many more beds than the former. However, be this as it may, the predominance of underthrusts is firmly established as far as these experiments are concerned. Chamberlin and Shepard[1] also concluded that the overfold and overthrust predominate over the underthrust and underfold.

Experiments 35 and 36 (Figs. 18 and 19) show conclusively that underthrusting will develop in plastic as well as brittle materials, while field observations substantiate the experimental results. Cross sections through the Jura Mountains of Europe show numerous underthrust faults, and minor folds and faults exposed in other regions exhibit this phenomenon as well. A tabulation of the over- and under-thrusts as shown in the fifteen cross sections of the Jura Mountains illustrated in Heim's[2] *Geologie der Schweiz* shows that there are 23 overthrust as compared with 13 underthrust faults based on the assumption that the active force came from the Alps. This ratio, 2.3 to 1.3, compares favorably with the results of these experiments which, as shown in the table on the previous page, is 2.8 to 1.6. The ratio of overfolds to underfolds in the Jura Mountains is essentially 3 to 1, since 25 of the former as compared with 8 of the latter can be counted in the fifteen cross sections of Heim's work. Combining the overfolds with the overthrust faults and the underfolds with the underthrust faults of the Jura Mountains the ratio is slightly more than 2 to 1, or, to be exact, 48 to 21.

The writer does not wish to place too much stress upon these figures, but it seems well to call attention to seeming agreement between the data from the Juras under these assumptions and the results of the experiments. It remains now to arrive at some logical reason for the failure to find underthrusting as common in previous experimental work. Many previously performed experiments in tangential stresses were carried on with differing amounts of removable overburdens. Naturally what goes on in these overburdens is generally not observable, nor is it recorded by photographs. As already pointed out, the underthrust fault planes as a rule develop next to the push-block *at the surface and extend downward no farther than the simultaneously developed overthrust fault plane*. Consequently if the top of the push-block is higher

[1]R. T. Chamberlin and F. P. Shepard, "Some Experiments in Folding," *Jour. of Geol.*, Vol. 31 (1923), No. 6, pp. 496-99.

[2]Albert Heim, *Geologie der Schweiz*, Tafel XXII-XXIV.

than the surface of the sediments under observation, so that it extends up into the overburden, it may be that none of the underthrust fault planes will reach the sediments under observation. For an example, in Figures 5 and 16, if all the material above *B* were removable overburden, the presence of the underthrust fault plane *BD*, as well as the upward extension of the overthrust fault plane *BC*, would not be observed or recorded by photograph. A similar condition may occur in nature, for example, where a mountain mass under observation has suffered great denudation so as to remove this upper portion in which the greater part of the underthrust element has developed. This may account for the relative or apparent lack of underthrust faults in many of the mountain systems studied. Another factor already alluded to is the tendency on the part of most experimenters to force the push-blocks too far into the sediments. This will necessarily obliterate the initial fault or shear planes for folding or shattering to such a degree that the original cone of shear and wedge frame-work becomes obscured.

DEVELOPMENT OF OVER- AND UNDER-THRUST FAULTS IN PAIRS

A very common phenomenon observed in many of the experiments was the development of an overthrust together with a corresponding underthrust. The conception of a wedge applicable to an entire uplift in which the side nearest the active stress is a plane or series of underthrust faults dipping away from the push-block, while the farther side is a plane or a series of overthrust faults dipping toward the push-block, has already been discussed. The same phenomenon is a characteristic development on a smaller scale when a relatively brittle layer is subjected to stresses. An underthrust fault plane may have, as its complement, an overthrust fault plane farther on; thus, a small wedge results (Fig. 34). If the underthrust fault plane is nearest to the side from which the active stresses came, then the small wedge will move upward with respect to the layer in question, while if the conditions are reversed, the wedge, bounded by over- and under-thrust planes, will move downward with respect to the layer or bed in question. The latter will be termed an *inverted wedge*. It is significant that there is a marked tendency for such pairs of fault planes to develop at an angle close to 45 degrees with respect to each other, although the angle with respect to the surface may vary. In this manner perfectly symmetrical wedges or *inverted wedges* may develop. Illustrations of such wedges are shown clearly in many of the experiments and a tabulation of their occurrence is given on page 846 (Fig. 34).

FIG. 33.—Surficial compression as observed through a plate-glass side. Notice the closely folded surface and the low-angle overthrust faults, one of which was deflected by a tension fissure dipping in the opposite direction, thus deflecting it backward and giving rise to a "discoidal" fault (see white line). High-angle underthrust breaks near the push-block.

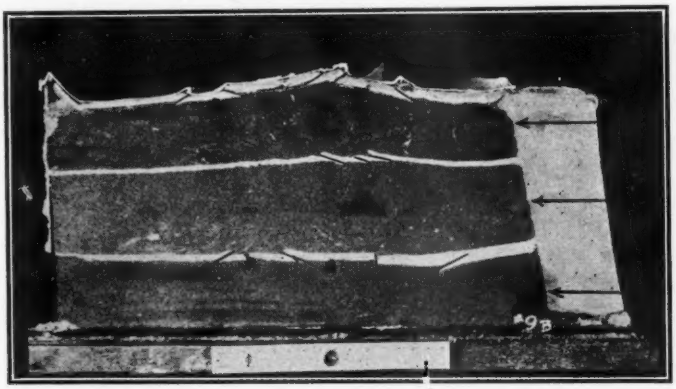

FIG. 34.—Experiment 9A, in which the artificial sediments were rigid enough to transmit forces to opposite resisting wall. Notice in particular the inverted wedges, *a* and *b*, and the upright wedge *c*. "Basin range structures" might have had an origin similar to wedges *a* and *b*.

Wedges of this type are a rather common phenomenon in the Jura Mountains of Europe. Cross sections of these are shown in Heim's *Geologie der Schweiz*.[1] Development of such over- and under-thrust fault

[1]See Heim's Plate XXIV, Section 11, where an inverted wedge at the extreme right, between Vuitteboef and Chamblon, is shown; and Plate XXIV, Section 13, at Vallie des Rousses; and Plate XXIV, Section 15, at Valserine. Two incipient upright wedges are shown on Heim's Plate XXIII, Section 10, at Siagnotte and Kette von Cornufoulet.

planes in pairs is closely related to the growth of fan-shaped folds. In fact, it is obvious that additional compression could cause faulting on the flanks of a fan-fold and thus develop an upright wedge, while an inverted fan-fold is a potential inverted wedge. Fold development may be entirely omitted in brittle materials and the wedge then forms immediately without passing through the fan-fold stages. Cadell[1] seemingly recognized the relationship between thrust faulting in pairs and fan-folds, since, in his conclusions, he stated,

> Fan structure may be produced by the continued compression of a simple anticline, also
>
> Thrust planes have a strong tendency to originate at the sides of the fan.

and

> This theory may also explain the origin of fan structure, and its accompanying phenomena, *including wedge structure.* (The italics are the writer's.)

If the fault planes bordering an inverted wedge were obscured in the field it is obvious that such a structure could very easily be interpreted as a fault-graben, and the suggestion might be ventured that possibly some of the supposed fault-grabens of the Great Basin area in Nevada are actually nothing but inverted wedges due entirely to tangential thrusts (Figs. 35 and 36).

SUGGESTED WORKING HYPOTHESIS

The idea of the wedge is not original with the writer. Experiments illustrating the development of the wedge and the cone were performed by Daubrée[2] many years ago. Experiments on the compression of building stone have been performed by investigators too numerous to refer to here individually. The apparent wedge shape of the Appalachian mountain orogeny was fully described by Chamberlin[3] as early as 1910. In 1925 Chamberlin[4] presented his "Wedge Theory of Diastrophism" in which he concluded that

> Field studies on the depth of folding, laboratory experiments in faulting with analysis of stress-strain relations, and the two-sided character of various mountain systems have led to the conclusion that the wedge-shaped block is the typical form of compressed mountain ranges. The typical wedge apexes downward in the middle of the deformed zone, ...

[1] Henry M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. of Edinburgh*, Vol. 35 (1888), p. 337.

[2] A. Daubrée, *Études synthetiques de géologie experimentale, T. I. P. 316,* Plate 2, Fig. 3.

[3] R. T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. of Geol.*, Vol. 18 (1910), No. 3, pp. 228-51.

[4] *Jour. of Geol.*, Vol. 33 (1925), No. 8, pp. 755-92.

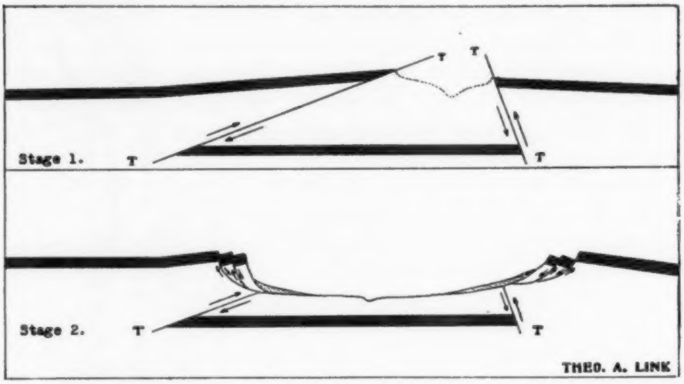

FIG. 35.—Illustrating a deformational and erosional history *possibly* applicable to some basin range structures. Stage 1, tangential compressive forces giving rise to an "inverted wedge." Stage 2, erosion and under-cutting causing landslide slumping and normal faulting obscuring the original thrust faults, with deposition of débris in the basins, thus obscuring all evidence of true deformational history.

On pages 764 to 771 of his paper Chamberlin reviews adequately seeming exemplifications of the wedge theory. As lack of space prevents discussion of this phase, the reader is referred to Chamberlin's paper for that information.

The conception of the *cone of shear* was not presented by Chamberlin. The writer's method of presenting the evidence in favor of the wedge is slightly different. This, in particular, is true with regard to the cause of asymmetry exhibited by some of the wedges. The writer believes that the *cone of shear* is an important corollary to the wedge conception. As pointed out in the foregoing discussions, the degree of metamorphism inside the cone is much greater than within the wedge. The cone develops first and the wedge later. This is regarded as accounting for the fact that the areas adjoining the mountain wedges on the side from which the active stresses were operative are almost invariably much more metamorphosed than the strata within the wedge, and leads to a working hypothesis which, in the opinion of the writer, is of paramount importance.

Given an orogenic unit, closely folded and faulted, striking north and south, exhibiting an asymmetrical wedge defined on the east side by low-angle thrust faults dipping westward, and on the west by high-angle thrust faults dipping eastward, bordered on the west side by highly metamorphosed strata, and on the east side by relatively un-

disturbed strata,—such an orogenic unit would, on the basis of these experiments, indicate that the operative forces acted from west to east because of the greater degree of metamorphism found on the western border corresponding to the cone; therefore, the low-angle westward-dipping thrust faults are *over*-thrusts, and the high-angle eastward-dipping faults are *under*-thrusts. Furthermore the wedge in question was developed by surficial compression dying out rapidly at depth as indicated by the closely folded nature of the uplift.

On the other hand, given a broad plateau- or dome-like orogenic unit, striking north and south, exhibiting an asymmetrical wedge defined on the east side by a high-angle thrust fault dipping westward, and on the west side by low-angle thrust faults dipping eastward, bordered on the west by deep-lying highly metamorphosed strata, and on the east side by relatively undisturbed rocks,—such a unit would, on the basis of these experiments, indicate that the operative forces acted from west to east because of the greater metamorphosed west-bordering strata; consequently, the high-angle westward-dipping faults are *up*-thrusts, and the low-angle eastward-dipping faults are *down*-thrusts. The plateau-like wedge in question indicates deep-seated compression. Normal faulting and possibly fault-grabens would probably be found on this broad uplifted plateau or domal area.

The same method of attack is applicable to a symmetrical wedge. The

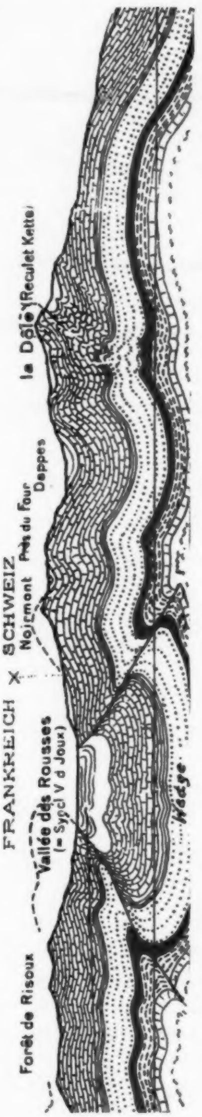

FIG. 36.—Partial section through the Jura Mountains of Switzerland and France illustrating a conspicuous "inverted wedge." Taken from Heim's *Geologie der Schweiz.*

factor of prime importance is to determine the position of the highly metamorphosed strata which correspond to the area of the cone of shear directly in front of the push-block in the laboratory experiments. Kober's[1] theory postulating a "Vorland" (foreland) of more resistant rocks on both sides of geosynclinal tracts squeezing the latter between them does not entirely fit the conditions on the earth's surface. Relatively undisturbed strata are ordinarily encountered on one side of an orogenic unit. There are, admittedly, some units where "forelands" are found on both sides, but this is not the rule. The writer leans decidedly toward the conception that compression is active[2] only from one side with passive resistance from the other. If it is admitted that there is more compression from the one side than from the other this amounts to admission of active compression from one side only, in the same way that an aeroplane, flying at a rate of 60 miles an hour against a head wind of 70 miles an hour, would be moving backward at a rate of 10 miles an hour. We observe the *result* of compression in mountain chains just as we observe the *result* of the stronger head wind forcing the plane backward.

CONCLUSIONS

If the reasoning in this article is sound, and if the results observed in the scores of experiments which were performed have any value or significance, then it should be possible to speak of *over-* or *under-*thrusts without an assumption, provided the mountain system under observation is exposed to view at least in several good cross sections or preferably as a complete unit.

The following table indicates the writer's version of the nature and direction of operative forces giving rise to some of the better known mountain systems.

A detailed discussion of this table would lead to an attempt at disentangling the genetic relationship between different portions of what are to-day regarded as the same mountain systems. This is particularly true of the Rocky Mountains which extend from Mexico to Alaska. This system does not exhibit the same structural relationship throughout its entire length. The Colorado Rockies differ from the northern Mon-

[1]Leopold Kober, *Der Bau der Erde*, Gebrüder Borntraeger, Berlin, 1921.

[2]This attitude is held in spite of the "time honored adage of mechanics that 'action and reaction are equal.'" (This *Bulletin*, Vol. 11, No. 11 (November, 1927), p. 1,233.) The mention of this "time honored adage" here is about as "apropos" as a combination of two such adages, as, "a stitch in time saves two in the bush." In experiments there is a distinct difference between what happens in front of the push-block and in front of the resisting wall.

TABLE I

Mountain System	General Direction of Forces	Nature of Forces
1. Rocky Mountains	West to east	Relatively deep-seated in southern United States. Surficial in Montana and Alberta
2. Appalachian Mountains	Southeast to northwest	Surficial during Permian revolution. Deep-seated during post-Cretaceous
3. Sierra Nevada Mountains of California	Southwest to northeast	Relatively deep-seated
4. Jura Mountains of Europe	Southeast to northwest	Surficial

tana and Alberta Rockies. The Mackenzie Mountains of the Northwest Territories and the Endicott Range of Alaska, which are also regarded as the northwesterly extension of the Rockies, are again a different kind of structural unit. Space will not permit the discussion of such problems here. The writer's main purpose in this paper is to deal with what appear to be fundamental facts, as revealed by experiments, which seem to be applicable to fairly well known orogenic units.

A SIMPLE DERIVATION OF THE WORKING EQUATIONS OF MAGNETIC VARIOMETERS FOR VERTICAL AND HORIZONTAL INTENSITY[1]

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ABSTRACT

Derivations of the working equations of a local magnetic variometer in general use in the field are ordinarily based upon complicated theoretical considerations, the use of Lagrange's equations, etc. These methods call for more theory than is generally at the command of persons using the instrument. The author presents a simple derivation involving nothing more than elementary physics.

At present somewhat general use is being made of magnetic local variometers or magnetic balances in the investigation of underground deposits and structures. Many users of these instruments have expressed to the writer their inability to follow the derivation of the working equations. These derivations ordinarily are based upon rather complicated general considerations involving somewhat more theory than the average reader possesses. For this reason a simple discussion involving nothing more than elementary physics would seem to be worth while.

The simple theory here given is for the purpose of deriving directly the formulæ used in making observations with the balances and does not go into the numerous corrections, actual and possible. These have been fully discussed by C. A. Heiland and P. Duckert.[3] Dr. Heiland[4] has also given a simpler treatment, but he starts with an equation previously derived by general methods.

VERTICAL INTENSITY VARIOMETER

We shall start with a schematic representation of the swinging system which is a cubical metal block carrying two thin magnets and adjusting devices. The whole system oscillates about a quartz knife edge

[1]Manuscript received by the editor, March 16, 1928.

[2]Dean, Graduate School, University of Colorado. Introduced by John L. Rich.

[3]*Zeits. für Angew. Geophysik*, August, 1924, and January, 1925.

[4]"Construction, Theory and Application of Magnetic Field Balances," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 12 (December, 1926), pp. 1189-1200.

turning on quartz cylinders. The center of gravity of the whole system lies a little below the knife edge and a little on one side of it, toward the negative pole of the magnet.

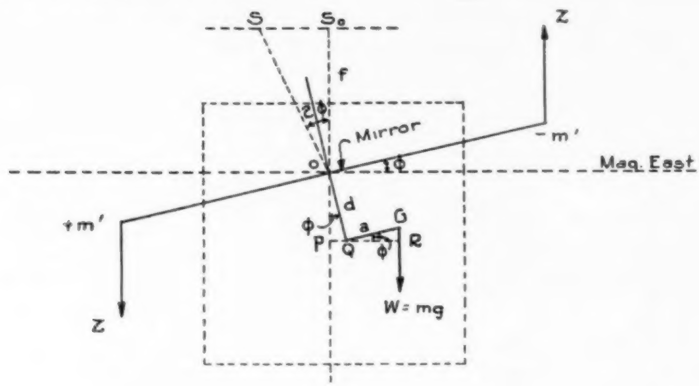

FIG. 1

In the vertical intensity variometer, or balance, the magnets remain always nearly horizontal. Hence in Figure 1 the tipping is greatly exaggerated. Since the instrument is used with the magnets perpendicular to the magnetic meridian, the only effective magnetic force acting is the vertical component Z of the earth's magnetic field, and the angular displacement is directly proportional to Z if we assume, as is usually done, that the other characteristics of the instrument remain constant.

In Figure 1 we shall take

$+m'$ and $-m'$ as the poles of a single magnet. The line joining them, $2l$ in length, is the axis of the magnet.

Z as the vertical component of the earth's field.

O as the axis of the knife edge, perpendicular to the paper.

G as the center of gravity of the oscillating system, symmetrical with respect to the system except for its displacement toward the south pole.

d as the vertical distance of the center of gravity from O when the system is horizontal.

a as the horizontal distance of the center of gravity from O toward the south pole $(-m')$ when the system is horizontal.

Zm' as the magnetic force acting on one end of the magnet.

$W = mg$ is the weight of the system acting at the center of gravity G.

In Figure 1 the mirror is shown as located in the plane of the knife edge whereas it is really a little above it. This is a simplification which does not appreciably affect the argument.

The whole oscillating system will come to equilibrium under the action of two torques, one due to the earth's magnetic field tending to turn it counter-clockwise, the other due to gravity tending to turn it clockwise. Equilibrium will occur at some angle ϕ which is always very small. Hence, taking moments about O and remembering that there are two parallel magnets, we have

$$2\ (Zm' \ .\ 2l) \cos \phi = W \times PR = W\ (PQ + QR)$$

But by definition

$4\ m'l = M$, the magnetic moment of the magnetic system

and $PQ = d \sin \phi$

$QR = a \cos \phi$

$W = mg$

Hence

$$MZ \cos \phi = mg\ (d \sin \phi + a \cos \phi)$$

or $$\tan \phi = \frac{MZ - mga}{mgd}$$

Also from the figure we have

$\tan 2\phi = \dfrac{S - So}{f}$ and when ϕ is small we can get

$\tan 2\phi = 2 \tan \phi$. Hence

$\tan \phi = \dfrac{S - So}{2f}$ where f denotes the focal length of the telescope objective. Therefore

$$\frac{S - So}{2f} = \frac{MZ - mga}{mgd}$$

or $$S - So = 2f \left[\frac{MZ}{mgd} - \frac{a}{d}\right]$$

Now if *So* is the zero of the scale we can call the interval $S - So$ simply S and write

$$S = 2f\left[\frac{MZ}{mgd} - \frac{a}{d}\right]$$

If we now take the instrument to some place where the vertical intensity is Z' instead of Z we shall get a new reading

$$S' = 2f\left[\frac{MZ'}{mgd} - \frac{a}{d}\right]$$

and the difference between S' and S is then

$$S' - S = \frac{2fM\,(Z' - Z)}{mgd}$$

or $$Z' - Z = \frac{mgd}{2fM}\,(S' - S)$$

where $\frac{mgd}{2fM}$ is a constant for each instrument, called the scale-value of the instrument. It denotes the force, in absolute units, necessary to produce a deflection of one scale division.

If we call it e we can write

$$Z' = Z + e\,(S' - S)$$

which is the usual formula for use in observing. Of course the result, Z', must be corrected for all variations which ordinarily apply in the use of the instrument.

VARIOMETER FOR HORIZONTAL INTENSITY

This instrument measures variations in the value of H, the horizontal component of the earth's field. The magnets stand approximately vertical, instead of being horizontal as in the variometer for Z, and never move very far from this position. The motion of the whole system takes place also in the magnetic meridian instead of in the plane perpendicular to it as in the case of the other instrument.

Figure 2, also greatly exaggerated as to the angular displacement and most of the distances, shows the action of the forces.

The lettering of the figure is the same as in Figure 1. The north pole of the magnet is below the knife edge at $+m'$. Conditions are much the same as for the other case except that the center of gravity, G, lies

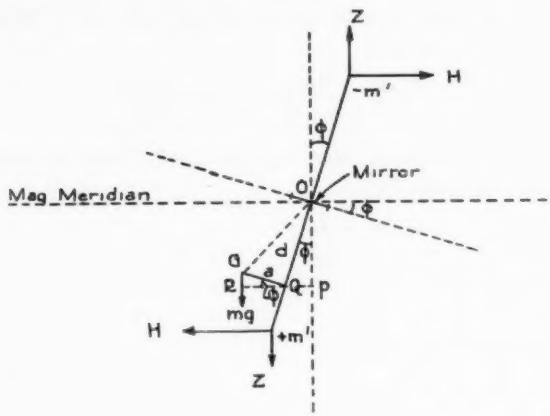

FIG. 2

below and to the left of the point of support. Also in this case both the horizontal component, H, and the vertical component, Z, are effective and enter into our formulæ. Hm' is the predominant force, however, because its lever arm about O is very much greater than that of Zm', since the angle ϕ is usually measured in minutes.

Taking moments about O as before, we get

$$HM \cos \phi = ZM \sin \phi + mg \times RP$$
$$= ZM \sin \phi + mg\,(RQ + QP)$$
$$= ZM \sin \phi + mg\,(a \cos \phi + d \sin \phi)$$

or $HM = ZM \tan \phi + mga + mgd \tan \phi$

Hence

$$\tan \phi = \frac{HM - mga}{ZM + mgd}$$

But as before; $\tan \phi = \dfrac{S - So}{2f}$

and $S - So = 2f \left[\dfrac{HM - mga}{ZM + mgd}\right]$

Now if we move the instrument to a place where H is different, say H', we get a new reading,

$$S' - So = 2f\left[\frac{H'M - mga}{ZM + mgd}\right]$$

where Z will, in general, change to Z' also. The change in H given by the two preceding readings is

$$S' - S = 2f\left[\frac{M(H' - H)}{ZM + mgd}\right]$$

Hence

$$H' - H = \frac{ZM + mgd}{2fM}(S' - S)$$

or $H' = H + e(S' - S)$ whence $e = \dfrac{ZM + mgd}{2fM}$

This last formula is the one usually given as the working formula, but it will be noticed that the scale-value, e, is no longer a constant but varies with Z. This is what makes the horizontal-component variometer less simple to use than the vertical one. Readings must be corrected as usual for: (1) temperature changes, (2) variation of magnetic field, (3) possible displacement of center of gravity, (4) possible permanent changes in the magnetic moment of the magnet system (that is, in M), and (5) variation of Z which enters the expression for e.

GEOLOGICAL NOTES

JOINTING IN LIMESTONES AS SEEN FROM THE AIR

In the course of an airplane trip from Tulsa, Oklahoma, to Wichita, Kansas, by way of Bartlesville, which it was my good fortune to make recently at the invitation of our first vice-president, Mr. J. E. Elliott, attention was irresistibly drawn to the geological features visible from the air. Most striking of these was the remarkable jointing displayed by certain limestones where they were exposed at the surface or under a thin cover of soil.

About 6 miles north of Skiatook this feature was most clearly shown. Over an area of several square miles, a thin limestone, probably the Dewey member of the Drum group, forms the capping of numerous isolated mesas, and is exposed in a wide outcrop on all projecting points. From a height of about 1,800 feet the entire joint pattern in this limestone could be seen with the greatest distinctness.

The joints are revealed by grass and other vegetation growing in the fissures. Where there appeared to be a considerable thickness of soil, the joint pattern could still be distinguished by the lines of darker green in the vegetation along the joint planes. Though the details of the joint pattern differed in different places, it was noticed that the pattern generally consisted of two principal systems intersecting at approximately right angles. Directions, relative prominence of the two principal systems, and spacing were variables. Other groups of joints making different angles with the principal systems were noticed here and there, the whole forming a network of the greatest beauty and interest.

In flying over the route from Bartlesville to Wichita the same features were noticed at many places wherever the limestone outcrops were wide, as on the tops of mesas, or on points between adjacent ravines. The jointing was especially prominent in what appeared to be the upper limestone of the Oread where it was crossed in T. 28 N., R. 9 and 10 E., Osage County, Oklahoma. In this locality, from a height of 3,000 feet, the entire joint pattern over several square miles could be seen in a single view. It happens that this territory is a thoroughly dissected topographic bench formed by the upper Oread limestone. The outcrops are wide, mesas are numerous, and the dissection is so thorough that

from a considerable height the joint pattern can be clearly projected across the valleys and the relatively narrow divides so that it merges into a connected whole. The joints, with their vegetation markers, are so clear from the air that they could be photographed readily.

Study of joint systems, such as these, from aerial photographs offers a field for interesting and, perhaps, important research on the relation of jointing to structure, for, presumably, the joint pattern is influenced by the structure. If an area like that north of Skiatook, or parts of T. 28 N., R. 9 and 10 E., were photographed from the air, and a very detailed structural map were made of the same area, the data would be at hand for determining this relation. Once the relations were worked out, they might then be applied in areas where exposures are less perfect.

Other geologic features noticed on the trip might be of interest. In the partly wooded sandstone area northwest of Bartlesville, underlain by rocks below the Oread limestone, several sandstone ledges could be followed for short distances, but no widely continuous outcrops could be distinguished. On the limestone areas, however, including all the territory underlain by rocks from the Oread limestone at the base to the Herington limestone at the top, outcrops are clearly distinguishable. Even where the white limestone fragments or the outcropping ledge cannot be seen, the position of the ledge is commonly revealed by characteristic vegetation.

From a height of 3,000 feet the minor structures of the area could not be seen, though here and there suggestions of structure were detected in the relation of the outcrops to drainage lines. The Dexter anticline could be seen without difficulty.

A striking feature of the "Flint Hills" country of southern Kansas and northern Osage County, as seen from the air, is the intricate pattern of the minor drainage. It is likely that a relation of this drainage network to structure could be worked out from aerial photographs supplemented by ground work.

JOHN L. RICH

OTTAWA, KANSAS
July, 1928

DISCUSSION

METHODS OF APPLIED GEOPHYSICS

The review of my *Methods of Applied Geophysics* in Vol. 12 of this *Bulletin*, No. 5 (May, 1928), pages 561-62, by C. A. Heiland, compels me to correct some impressions that may have been gained by readers of the review.

The reviewer says the author's statement that his book will be a truly scientific paper "may perhaps be misinterpreted in view of the fact that there are a number of formulas and figures which have been taken from other geophysical publications without credit being given to them." I wish to state that due credit is given to everyone who contributed to applied geophysics. The fact that forty-seven scientists are mentioned may be sufficient in this connection. The reviewer is in error, when he believes that uncredited formulas in my book which he may find in other geophysical papers are the product of only that author whose work he may have read. All these are fundamental formulas which may be found in every textbook of physics or mathematics or which can be easily derived by any mathematician or physicist. On the other hand, the author gave many new equations of great importance which are uncredited, as they may be derived by any competent geophysicist. That which is said with reference to uncredited formulas applies also in the case of figures. All these figures illustrate long-known physical facts; further, credit is not claimed for all original figures given in the book, for the same reason.

In reply to the statement, "the reviewer does not quite agree with the author that pendulum measurements are inadequate for geophysical investigations," I would refer the reader to the sentence on page 7 of my book where I intended to emphasize the practical limitations of the pendulum,—"For *practical* geophysical purposes, the pendulums have the disadvantage of giving gravity or its change in only vertical direction....that the measurement of the vertical component alone is inadequate for *economical* geophysical investigations, for a quick survey, as this component does not indicate the direction of the gravitational disturbance in which the deposit is to be found." It is of common knowledge that the torsion balance will indicate, for instance, a salt dome several miles away from it, while the pendulum is effective only directly above it; and further, that the sensitivity of the torsion balance is one million times greater than that of the pendulum, the sensitivity of which, in most cases of practical exploration, is insufficient. The value of the pendulum for geophysical investigations was given by the author in the *Oil Weekly*, March 18, 1927.

The statement that "The principle of the various seismographs used in seismic stations is also illustrated" gives an incorrect impression, as seven figures on page 44 illustrate the principle of field seismographs also, being explained in the paragraph, Field Seismographs.

I considered it superfluous to give a table of magnetic susceptibilities of rocks, as these are very unlike in different places, due to their different content

of iron substances, as mentioned in my book. The mineral, ilmenite (ferrous titanite, $FeTiO_3$) was intentionally omitted because the presence of titanium makes it valueless as an ore. Pyrrhotite and limonite are mentioned, the first on page 2, and as magnetic pyrite on page 58, and the second (hydrous ferric oxide), also called brown hematite or hydro-hematite, under the last name on page 51. The reviewer states that the magnetism of granite is a fact for magnetic oil exploration. He fails, however, to substantiate this by giving the necessary susceptibility data. The possibilities of magnetic prospecting for precious metals are given on pages 2 and 52. That siderite (ferrous carbonate, $FeCO_3$) disintegrates under ordinary conditions to hematite (Fe_2O_3) and limonite ($2Fe_2O_3 \cdot 3H_2O$) is of common knowledge. Its disintegration to greenstone was mentioned because such disintegrated siderite was magnetically located in Germany.

The statement is made in the review, "The reviewer does not agree with the author that the theory is obsolete which conceives that the deposit is equivalent to one permanent magnet or several of them." I stated on page 53, "According to the conception at that time, a permanent magnetism of the deposits with two punctiform poles was adopted for the theoretical calculations, but these conceptions cannot satisfy and are not to be applied in searching for tectonic structures and salt masses. A theory, to explain the magnetic anomalies measured on the surface, must generally issue from the magnetic potential of inducted masses." Based upon many experiences, it is to-day the opinion of a majority of geophysicists that the cause of magnetic anomalies is the induced magnetism of embedded masses produced by the earth's magnetic field, and that, consequently, the acceptance of magnetic induction must be the foundation of a general theory for calculating magnetic disturbances of subterranean deposits. Even in cases where the induced magnetism has become permanent in the deposit, such permanent magnetism does not produce other values than those based upon the induction theory, if the deposit maintains the same position it had at the time of its magnetization. Further, the induction theory is applicable only when magnetite or other iron substances with greater coercivity came, after their primary magnetization, irregularly into the strata.

The author does not see the necessity of including in a modern treatise the old known formulas of Thalen (1875), which are based upon the conception that magnetic deposits are identical with *bar* magnets; nor those of Smyth (1899), who considered the magnetic deposits as slab-like bodies and of *unlimited* thickness. The triple integral for the magnetic potential is included in the simplest form, and all who are not able to derive the forces from this integral would also be unable to read their complicated equations or to understand the course of the calculation, which would fill approximately half the book. Therefore, the forces (horizontal and vertical anomalies) are graphically illustrated for a globular body, anticline, and fault, by the author.

The author's statement that *relative* magnetic measurements are made exclusively in applied geophysics is based upon the fact that German and American geophysical companies and departments of oil companies use variometers for relative measurements in their exploration work for economical reasons. The fact that persons or institutes that own instruments for absolute measure-

ments occasionally use them for exploration does not seem to the author to alter this statement.

The geothermal method was intentionally omitted because it is practically valueless in *applied* geophysics due to the high degree of uncertainty. However important the geothermal studies may be for geophysical and geological purposes in determining the geothermic degree of the earth's crust, no earnest practical geophysicist would ever take the responsibility of making locations for drilling for commercially valuable deposits purely upon geothermic measurements, as it is a known fact that the earth's temperature varies uncontrollably from place to place, due to many known and unknown factors. Some of the known factors may be mentioned here: terrain conditions, air and gas currents within and above the ground, temperature changes in the ground produced by subsurface waters, variety and stratigraphy of rocks and their differing specific heats, subsurface moistures, chemical processes (oxidation) within the stones, and radioactive processes.

The reviewer comments on the absence of illustrations of a torsion balance and magnetic instruments. The author considers that such pictures belong in the catalogs of manufacturers and not in scientific papers.

E. Pautsch

Institute of Applied Geophysics
Houston, Texas
June, 1928

REVIEWS AND NEW PUBLICATIONS

Bodenablagerungen und Entwicklungstypen der Seen (*A Study of Lake Deposits*). By G. LUNDQVIST (Stockholm). Vol. 2 of Thienemann's "*Die Binnengewasser.*" E. Schweizerbartische Verlagsbuchhandlung, Stuttgart, 1927. 60 figs, 14 plates (mostly microphotographs), 3 tables, 124 pp.

A Swedish scholar named Hampus von Post made a good start in the study of lake deposits in 1862, but most of the progress in this field dates from 1917. At that time Naumann revised the methods of work and made real progress possible. Some peat geologists, notably Lennart von Post, exerted much influence on the limnologists. Dr. Lundqvist himself was persuaded by von Post to undertake the study of fossil lake deposits. He has developed many new methods, including a borer which gives a good core of the total thickness of the deposits. He considers his methods imperfect and his results incomplete, but they are certainly interesting and suggestive.

Many precautions are necessary to secure properly selected and uncontaminated cores. They are usually taken in series from the shore outward toward deep water. The distance between cores differs greatly with conditions, in some places being less than a meter and in others a hundred meters. Samples are taken from each core, not more than 20 centimeters apart. They must be studied while fresh.

A necessary part of the study of each core is an age-determination. The varve-method, applicable under some conditions, is generally considered unreliable unless carefully checked. Of all the methods proposed, a pollen-analysis is by far the best. It was devised by Lagerheim in 1909 and has been improved by several workers since. Dr. Lundqvist takes about 2 cubic millimeters of a sample, prepares a slide from it, and then counts 100-150 pollen grains. The figures for each species are reduced to percentages and plotted in curves. Since the pollen grains in the sediments mirror the forest succession that has prevailed over southern Sweden, and since this is already well known, a simple comparison with the standard curve gives the age-relations of the core under consideration. It is even possible to give several dates: 6,000 B. C., the culmination of the Ancylus stage of the Baltic; 4,500 B. C., the Litorina stage; and 500 B. C., an important change of the climate to less favorable conditions.

Fossil zones may be available, but are considered less trustworthy than the pollen zones, which were not influenced by varying chemical conditions.

Dr. Lundqvist has devised an objective method for determining the "structure" of a sample. He proceeds by determining the volume percentages of each constituent in a definite volume (2 cubic millimeters) of the sample. Many of the constituents are organic, including humus floccules, shell fragments, and micro-organisms; others are detrital minerals and chemical deposits. The results are shown in diagrams.

Microfossil analyses, which furnish a basis for many further investigations, are carried out by counting the number of individuals of each species in 1 cubic millimeter of material, and expressing the results simply as the number of individuals present. A percentage method, devised by Halden, is found less satisfactory in practice.

The classification of the sediments is considered one of the most difficult subjects of all, and it is certainly the most difficult to summarize briefly. Genetic terms being out of the question, the author adopts descriptive terms, such as Tongyttjaen, Seekreide, Kalkgyttjaen, and Seedy. Unfamiliar as these words sound, they are carefully defined, in terms of the amount, character, and color of the organic material, the proportions and kind of detrital and chemical constituents, and so forth. They are further illustrated by a series of microphotographs, and by numerous diagrams.

It is noteworthy that the early beds in a series are likely to be calcareous, the iron sediments, if any occur, being found in the upper part of the profile. There are many complicating factors, prominent among them the character of the bedrock in the vicinity of the lake, but the general rule holds. The reason seems to be that the more soluble constituents in the drainage area are dissolved out first, those less soluble later.

Dynamic factors are discussed at considerable length. Redeposition, due to boring organisms and other agents, seems to be less confusing than one might suppose. Waves and currents are important complicating factors, and their effects are illustrated with many diagrams and much discussion. Peat forms on protected shores, for example, the bottom is deeper near exposed shores, lateral currents develop bottom channels, and so forth. One of the more complicated diagrams illustrates the discontinuities in the bottom sediments of one lake, a most instructive exhibit. A long account is given of different types of transgression and regression, their causes, and their recognition in bottom deposits.

The final chapters discuss the relations of bottom deposits to the classification of lakes, and of the lakes of southern Sweden to the geology of the country. There is a bibliography of 69 titles, nearly all twentieth century publications.

This book shows in a striking way how far recent researches have carried the Swedish geologists in certain branches of sedimentation. The discussion of fundamental geological phenomena is clear and stimulating, and is based on an unusual amount of accurate data. No sedimentary petrographer can fail to read the book with interest, and to get from it suggestions of value in the solution of his own problems.

R. D. Reed

Alhambra, California
June, 1928

Kohlenpetrographisches Praktikum (Practical Petrography of Coal). By Erich Stach. *Sammlung naturwissenschaftlicher Prakitka*, Vol. 14. Gebrüder Borntraeger, Berlin, 1928. 196 pp., 64 figs. Price, 10.80 M.

A well written and illustrated book, not of direct use to the petroleum geologist, but of interest especially to workers with well cuttings. A brief

enumeration of the contents of the chapters will best furnish an idea of the value of the book.

The first six chapters deal with the technique of macroscopic and microscopic study of coal. Chapter 1 gives brief directions for correct sampling. The macroscopic study of coal is discussed in Chapter 2. The microscopic examination in reflected and transmitted light, as well as all the different methods of preparation of thin sections, is described in great detail in Chapters 3 and 4. A short summary of the study of coal with the X-ray forms the contents of Chapter 5. The microphotography of coal preparations is discussed in Chapter 6.

The second half of the book is devoted to the identification and classification of the different types of coal. The three main petrographic constituents of coal, glance coal (called Vitrit), mat coal (Durit), and mineral charcoal (Fusit), are described in Chapter 7. The types of coal and their petrographic distinction form the substance of Chapter 8. The definition and separation of pit-coal, brown-coal, and peat are given in Chapter 9; and a last short chapter, 10, deals with the petrographic examination of briquettes.

The whole tenor of the book clearly shows that the author aims to make it valuable to practical men in the coal industry.

CHARLES RYNIKER

TULSA, OKLAHOMA
June 30, 1928

"The Stratigraphy of the Pennsylvanian System in Nebraska." By G. E. CONDRA. *Nebraska Geological Survey Bulletin 1*, second series, 1927. 291 pp., 38 figs., 9 tables, 7 plates, index. Price, $0.75.

The Pennsylvanian in Nebraska lies on rocks ranging in age from Ordovician to Devonian. The upper limit is placed at the Cottonwood limestone, to conform to the usage of the United States Geological Survey, though the author is inclined to place it at the Wreford limestone.

The Pennsylvanian is exposed in eleven counties in southeastern Nebraska, east of Lincoln and south of Fremont. Exposures are found in stream valleys which have been cut through loess and drift, in the northern part of the area, and on the uplands in the southern part, where the mantle rock has been more generally removed.

In lithology, the Pennsylvanian of Nebraska is similar to the occurrences in Iowa, Missouri, and Kansas, being composed of shale, limestone, and sandstone, in volume as named. There are few sandstone beds.

The large subdivisions, Des Moines and Missouri groups, are as valid in Nebraska as in contiguous states. The former is known only in drill holes, and only part of the latter is exposed.

STRUCTURE

The major structural features are the Table Rock and Nehawka anticlines, which have a north-south trend, and are in vertical alignment, though slightly offset. They are separated by a faulted syncline, trending east-west.

The Table Rock anticline extends from the area south of Wamego, Kansas, to the vicinity of Nebraska City, Nebraska. It is underlain by pre-Cambrian granite at relatively shallow depths, and is the northern extension of the Granite Ridge. East of this anticline lies the parallel Brownville syncline, which is broken along the west side by the Humboldt fault, upthrown 100 feet or more on the west. Beds of the Shawnee formation are exposed on the Table Rock anticline; Permian rocks are found in the Brownville syncline.

The Nehawka anticline extends from the area northwest of Nebraska City to Omaha. The upper part of the Lansing formation is exposed along its axis.

STRATIGRAPHY

Des Moines group.—These rocks are not exposed in Nebraska, though they are found in wells. The Cherokee and Marmaton subdivisions are not recognized.

The average thickness of the Des Moines group is approximately 600 feet in its main outcrop area; is 896 feet at Forest City, Missouri; decreases toward the north and northwest to 120 feet at Nebraska City, Nebraska, 116 feet at Nehawka and Weeping Water, 110 feet at Omaha, and 62 feet at Lincoln. It likewise thins westward from Forest City to 100 feet at Du Bois, Nebraska.

Missouri group.—The Kansas City formation and the lower part of the Lansing formation are not exposed, but are recognized in wells. The top of the Lansing (Stanton limestone), the Douglas, Shawnee, and Wabaunsee formations are exposed.

Kansas City formation.—The same subdivisions of this formation are recognized as in Kansas and Missouri, except that the term "De Kalb" limestone is used in place of Drum.

The thickness in the Nehawka, Nebraska, well is 140 feet, and at Kansas City it is 196 feet. The thinning seems to occur in the upper half.

Lansing formation.—This formation is likewise subdivided as in Kansas and Missouri. In the latter state its total thickness is 120 feet. In the Nehawka well it is 60 feet.

The top of the Stanton limestone, upper member of this formation, is exposed on the Nehawka anticline. It is the oldest bed cropping out in Nebraska.

Douglas formation.—This formation is found in the vicinity of Omaha, on the Nehawka anticline. It is subdivided as in Kansas and Missouri, and, in addition, the five subdivisions of the Oread limestone are given names for the first time.

The section at Nehawka, Nebraska, is as follows:

SUBDIVISIONS OF DOUGLAS FORMATION

Oread limestone	*Feet*
Plattsmouth limestone	28-30
Heebner shale	5
Leavenworth limestone	1½
Snyderville shale	11
Weeping Water limestone	7-13
Lawrence shale	
Iatan limestone	
Weston shale	

The total thickness of the Douglas is 294 feet at Lawrence, Kansas, and 125 feet at Nehawka, Nebraska.

Shawnee formation.—These rocks are exposed in a large area on the Nehawka anticline, on the axis of the Table Rock anticline, and in the southeast corner of the state.

The same members are recognized as in Kansas and Missouri, with several subdivisions.

Condra disagrees with Hinds and Greene[1] in regard to the position of the top of the Shawnee, placing it 80 feet lower than they did. He states that they miscorrelated the Tarkio and Burlingame limestones of the Wabaunsee formation.

The Shawnee formation in Nebraska is subdivided as follows (descending order):

SUBDIVISIONS OF SHAWNEE FORMATION

Scranton shale member
1. Silver Lake shale
2. Rulo limestone
3. White Cloud shale
4. Limestone
5. Shale
6. Cass limestone
7. Plattford shale
8. South Bend limestone
9. Rock Lake shale

Howard limestone member
1. "Louisville" limestone
2. Kiewitz shale
3. Church limestone

Severy shale member
1. Shale
2. Nodaway coal
3. Shale

Topeka limestone member
1. Coal Creek limestone
2. Holt shale
3. Du Bois limestone
4. Turner Creek shale
5. Curzen limestone

Calhoun shale member
1. Iowa Point shale
2. Meadow limestone
3. Jones Point shale

Deer Creek limestone member
1. Ervine Creek limestone
2. Mission Creek shale
3. Haynies limestone
4. Larsh shale
5. Rock Bluff limestone

Tecumseh shale member
1. Shale
2. Cedar Creek limestone
3. Shale

[1] *Missouri Bur. Geol. and Mines*, Vol. 13, 1915.

Lecompton limestone member
1. Avoca limestone
2. King Hill shale
3. Cullom limestone
4. Queen Hill shale
5. Big Springs limestone
6. Doniphan shale
7. Spring Branch limestone

Kanwaka shale member

Wabaunsee formation.—This formation is exposed in the largest area of all Pennsylvanian formations in Nebraska. The subdivisions differ slightly from those in Kansas and Missouri, and the members are further divided. The top of the Wabaunsee is put at the Cottonwood to conform to the usage of the United States Geological Survey, but Condra prefers to place it at the Wreford limestone.

The author also thinks that the Kansas geologists have mistaken the Tarkio for the Emporia limestone, and that Hinds and Greene in Missouri were in error in correlating the Tarkio with the Burlingame limestone.

The Wabaunsee formation is subdivided as follows (descending order):

SUBDIVISIONS OF WABAUNSEE FORMATIONS

	Nebraska		*Kansas*
	Eskridge shale member		Eskridge shale member
	Neva limestone member		Neva limestone member
	Elmdale shale member		Elmdale shale member
	1. Roca shale		
	2. Howe limestone		
	3. Bennett shale		
	4. Glenrock limestone		
	5. Johnson shale		
	6. Long Creek limestone		
	7. Hughes Creek shale		
	8. Houchen Creek limestone		
	9. Stine shale		
	Americus limestone member		Americus limestone member
	Admire shale member		
	1. West Branch shale		
	2. Falls City limestone		
	3. Aspinwall shale		
	4. Brownville limestone		
	McKissick Grove shale member		Admire shale member
	1. Poney Creek shale		
	2. Dover limestone		
	3. Table Creek shale		
	4. Maple Hill limestone		
	5. Pierson Point shale	?	
Nemaha Beds	Tarkio limestone member		Emporia limestone ?
Nemaha Beds	Willard shale member	?	Willard shale ?
Nemaha Beds	Emporia limestone		Emporia limestone member
Nemaha Beds	Humphrey shale member		Willard shale member
Nemaha Beds	1. Auburn shale		
Nemaha Beds	2. Wakarusa limestone		
Nemaha Beds	3. Soldier Creek shale		
Nemaha Beds	Burlingame limestone member		Burlingame limestone member

The report contains a large number of very detailed, measured sections of exposed rocks, and six cross sections are shown: along Missouri River from Leavenworth, Kansas, to Omaha, Nebraska; along Big Nemaha River, from its mouth to about 12 miles west of Du Bois; up Little Nemaha River from its mouth to Brock; from Union to Weeping Water; up Platte River from its mouth to Ashland; and from Roca to Bennett.

It also contains four detailed logs, with correlations, of wells drilled near Nehawka, near Lincoln, at Du Bois, Nebraska, and at Forest City, Missouri.

The Nehawka well passed through Pennsylvanian, Mississippian, Devonian(?), Silurian, Ordovician, and Cambrian, and found pre-Cambrian quartzite from 1,567 to 1,828 feet.

The Lincoln well likewise encountered pre-Cambrian quartzite from 2,192 to 2,463 feet. The Du Bois well passed from rocks of the Des Moines group into reddish granite from 558 to 565 feet. The Forest City, Missouri, well found Mississippian, Devonian, and Silurian beneath the Pennsylvanian.

Four very small-scale maps are given, showing towns, railroads, and drainage ways in the Pennsylvanian area of Nebraska; outcrop areas of the Des Moines and Missouri groups in Iowa, Missouri, Nebraska, Kansas, and Oklahoma; locations of structural features; locations of cross sections; and the areal extent of the different formations of the Pennsylvanian in Nebraska.

The final chapter contains the author's ideas of the interregional correlation of the Nebraska Pennsylvanian with the occurrences in other parts of the United States.

A little might have been added to this report by the use of a larger-scale map, showing the areal distribution of the formations, and a general tabulation of the stratigraphic units, with their equivalents in adjacent states.

It is a very excellent work, and is highly authoritative, since it is based on extensive field work, not only in Nebraska, but also in Kansas, Missouri, and Iowa.

This report makes a valuable companion volume to the reports of the Iowa Geological Survey, Vol. 13 (1915) of the Missouri Bureau of Geology and Mines, Vol. 9 (1909) of the University Geological Survey of Kansas, and *Bulletin 3* (1917) of the Kansas Geological Survey.

It emphasizes the unity and uniformity of the Pennsylvanian deposits in these four states, and the applicability of a general subdivision and nomenclature.

It is well known that synchronous beds are exposed in northern and central Oklahoma, though their exact relationships to their northern equivalents are not, as yet, satisfactorily established.

It is to be hoped that at least the groups and formations may be worked out for the Oklahoma rocks, in such a way that equivalent beds in these five states may be known and designated by the same names, and that a volume similar to this one may be written for Oklahoma.

The Texas Survey has already produced an excellent report on the Pennsylvanian of that state (*Bulletin 2132*, 1921), and an Oklahoma volume would complete the discussion for the Mid-Continent province.

ROBERT H. DOTT

TULSA, OKLAHOMA
July, 1928

Petroleum Development and Technology in 1927. By the PETROLEUM DIVISION, American Institute of Mining and Metallurgical Engineers, Inc., 29 West 39th Street, New York, N. Y., 1928. 844 pp., illustrated, cloth. 6 x 9 inches. Price, $6.00.

The Petroleum Division of the A. I. M. E. presents its digest of petroleum development and technology in 1927. The book is composed of papers and discussions by more than 200 engineers and geologists, well qualified by experience to handle their particular subjects.

Papers on production engineering occupy about half of the volume and 100 pages of this group are given over to the chapter on Air-Gas Lift. It is probably appropriate that so much space should be devoted to these subjects inasmuch as improved production methods—the air-gas lift in particular—were the immediate and principal causes of overproduction, which has been the outstanding feature of recent petroleum development.

Other chapters in the production group are Gas-Oil Ratios, Electricity in Oil Fields, Handling Congealing Oil and Paraffin, Increasing the Extraction of Oil, Sucker-Rod Strains and Stresses, and Deep-Well Drilling Technique.

There is a chapter of round-table discussions on Petroleum Engineering Problems, containing a special digest and discussion of geophysical methods of prospecting, and two chapters on Engineering Education.

The papers on refining technology are classified under four chapters: Distillation Methods, Heat Utilization, Refining Control, and Refining Products and Problems.

Two chapters on Production Development in 1927, covering domestic and foreign fields, are written for the most part by geologists.

Three important chapters are grouped under Petroleum Economics, namely, Petroleum Products, Crude Petroleum, and Export Trade.

This annual publication is of course a welcome volume of information for engineers and geologists, as it records their progress in efficiency. The presence of a goodly number of names of company executives among those contributing valuable discussions is also welcomed by technologists, as it indicates the recognition and success of applied science.

The volume is, however, much more than a report of successful progress; an important message is contained in the latter part of the book—an analysis of the troubles of the industry, sounding a warning against uncontrolled competitive drilling and production. In his article on the "Trend of the Petroleum Situation," Mr. Pogue reviews the several ways by which the over-supply of oil was stimulated. He says in part, "Perhaps, when viewed in its longer perspective, 1927 will stand out as the turning point in the economic policy of the petroleum industry, when the technique of rationalizing production made its initial claim for recognition."

The economic discussions may be profitably read by executives and directors of petroleum producing companies, for they contain a real message to those who are forming the policies and guiding the operations of one of our largest industries.

J. P. D. HULL

TULSA, OKLAHOMA
July, 1928

RECENT PUBLICATIONS

GENERAL

Oil and Petroleum Year Book (Oil and Petroleum Manual), 1928, by Walter E. Skinner, 15 Dowgate Hill, London, E. C. 4. Reference book of the oil industry, containing list of companies and directors. 430 pp. Demy 8vo. cloth. Price, 8s, 6d, postpaid.

Petroleum Development and Technology in 1927, by many authors. Papers on production engineering, refining technology, production, petroleum economics, and engineering education. American Institute of Mining and Metallurgical Engineers (Petroleum Division), 29 West 39th Street, New York, N. Y., 1928. 844 pp., illustrated. Cloth. Price, $6.00.

"Handbook of Petroleum, Asphalt, and Natural Gas," by Roy Cross. *Bulletin 25, Kansas City Testing Laboratory*. Revised 1928 edition. 830 pp., 215 illus. Fabrikoid, $7.50. Limp leather, India paper, $10.00, postpaid.

Petroleum, by Albert Lidgett. Sir Isaac Pitman & Sons, Ltd., Parker Street, Kingsway, W. C. 2, London. Revised and enlarged. 172 pp., 37 illus. Demy 8vo., cloth gilt. Price in Great Britain, 5s.

GERMANY

Geologie Deutschlands. Lager-Katalog Nr. 196, Max Weg, Leipzig. 295 pp.

ILLINOIS

The following publications may be obtained from the State Geological Survey, Urbana, Illinois:

"Oil and Gas Development and Possibilities in East-Central Illinois,—Clark, Coles, Douglas, Edgar, and parts of Adjoining Counties," by L. A. Mylius. *Bulletin 54*. Approx. 200 pp., 31 maps and cross sections. Price $1.50.

"Recent Development on the Ayers Anticline" and "Recent Drilling Northwest of St. Francisville, Lawrence County, Illinois," by A. H. Bell. *Illinois Petroleum No. 16*. Price, $0.25.

NEW MEXICO

Structural Map of Artesia Oil Field, by C. E. Dobbin, Foster Morrell, E. A. Hanson *et al*. U. S. Geological Survey, Washington, D. C., and Room 332, Federal Building, Roswell, New Mexico.

OKLAHOMA

"Oil and Gas in Oklahoma: Nowata and Craig Counties," by Edward Bloesch. *Oklahoma Geological Survey Bulletin 40-EE*. Norman, Oklahoma, June, 1928. 30 pp., 2 figs., 1 plate. Price, $0.30.

POLAND

"Polish Oil and Gas Fields in the Carpathians and on the Foreland," by K. Tolwinski. *Bulletin 16, Geological Survey of Poland*, Boryslaw, 1928. Text in Polish and French; 16 pp. Map in Polish and English; scale 1:500,000. Shows also pipe lines, refineries, and potash, salt, and ozokerite mines.

TEXAS

The following publications may be obtained from the Bureau of Economic Geology, University of Texas, Austin:

"The Geology of Cooke County," by H. P. Bybee and F. M. Bullard. "Petroleum Developments in Cooke County," by E. M. Hawtof. *Bulletin 2710* (March, 1928). 170 pp. Illus. Price, $0.75.

"Igneous Rocks of the Balcones Fault Region of Texas," by John T. Lonsdale. *Bulletin 2744*.

"The Cretaceous and Tertiary of Southern Texas and Northern Mexico and Cretaceous Ammonites from Texas and Northern Mexico," by Emil Böse and O. A. Cavins. *Bulletin 2748*. Illus.

"The Geology of Tom Greene County," by G. G. Henderson. *Bulletin 2807*. Illus.

TRINIDAD

"Geology of the Naparima Region of Trinidad (British West Indies)," by V. C. Illing, and

"Tertiary *Foraminifera* from the Naparima Region of Trinidad," by W. L. F. Nuttall. *Quarterly Journal of the Geological Society*, London, April 30, 1928. Pp. 1-116, illus.

THE ASSOCIATION LIBRARY

Headquarters acknowledges accessions:

FRANCE

From M. Jean Jung:
Les Indices de pétrole du Sundgau (Haute-Alsace)

TECHNICAL PERIODICALS

A complete list of exchange periodicals regularly received at headquarters is here printed. Current numbers are on the shelves of the Association library for the use of members. Photographs or other copies will be supplied at thirty-five cents a page. Write to Association headquarters, Box 1852, Tulsa, Oklahoma.

Annales des combustibles liquides (Paris)
Biuletyn-Stacja Geologiczna (Boryslaw)
Boletin de la Sociedad Geologica del Perú (Lima)
Bulletin of the Geological Society of America (Washington, D. C.)
California Oil World (Los Angeles)
Economic Geology (Lancaster, Pennsylvania)
Engineering and Mining Journal (New York)
Földtani Szemle (Budapest)
Geographical Review (New York)
Geologische Rundschau (Berlin)
Inland Oil Index (Casper, Wyoming)

Journal of Geology (Chicago)
Journal of the Institution of Petroleum Technologists (London)
Journal of Paleontology (Sharon, Massachusetts)
La revue pétrolifére (Paris)
Leidsche Geologische Mededeelingen (Leyden)
Mining and Metallurgy (New York)
Mining Journal (London)
National Petroleum News (Cleveland)
Oil Bulletin (Los Angeles)
Oil and Gas Journal (Tulsa)
Oil Engineering and Technology (London)
Oil Field Engineering (Los Angeles)
Oil Weekly (Houston)
Pan American Geologist (Des Moines)
Petroleum Age (Chicago)
Petroleum Bulletin (Moscow)
Petroleum Industry (Moscow)
Petroleum Times (London)
Petroleum World (Los Angeles)
Petroleum Zeitschrift (Berlin)
Proceedings of the Geologists' Association (Colchester, England)
Proceedings of the U. S. National Museum (Geology) (Washington, D. C.)
Quarterly Journal of the Geological Society (London)
Revue de géologie (Liége)
Senckenbergiana (Frankfurt a. M.)
Science (Lancaster, Pennsylvania)
Science News Letter (Baltimore)
Transactions of the Thermo-Technical Institute (Moscow)
Zeitschrift für praktische Geologie (Halle)

THE ASSOCIATION ROUND TABLE

MAINTAINING PERSONAL INTEREST IN THE ASSOCIATION

The executive committee is endeavoring to maintain personal contact with the members of the Association. The A. A. P. G. has grown remarkably since it was organized in 1917. Last year more members were admitted than during any other year in our history. We now have an enrollment of 2,000 members, living in 41 states and 29 foreign countries. Truly, more than ever, do we hold the rank of the largest organization of geologists. As our membership increases it is necessary to provide more means for serving the varied interests of the different members and groups. A new constitutional amendment provides for the election of district representatives so that the several geographic groups may express their needs more effectively in the business meetings of the Association. There is a tendency for local groups of members to organize as chartered sections of the Association. At present we have but one officially recognized section, the Pacific Section. Local geological societies whose membership requirements correspond with those of the A. A. P. G. might consider the advantages of affiliation for the sake of closer coöperation in the profession of petroleum geology. Technical groups in special phases of the profession, such as paleontology, microscopy, and geophysics, find that close relation to the Association is an asset. The Society of Economic Paleontologists and Mineralogists, composed of A. A. P. G. members, is an affiliated organization. Thus, although we find a diversity of activity, the Association is, in these several ways, fostering the mutual interests of many individuals and different geographic and technical groups within the larger body.

The officers this year are emphasizing the importance of making personal visits to the Association districts in order to give as many members as possible first-hand information about the work that is being done at headquarters and by the several committees, in accordance with the plans and instructions of the Association as voiced in the annual business meeting. President McFarland has made special visits not only to Oklahoma groups but also to the Kansas and Rocky Mountain districts, providing an opportunity to discuss Association affairs at meetings in Wichita and Denver. Other trips in the interests of the Association will be taken this fall. Vice-president Elliott has done much to encourage closer communication and coöperation by his air tour this spring from Los Angeles through the Mid-Continent and back by way of the American Petroleum Institute meeting at Colorado Springs. That trip was described in the At Home and Abroad department of the July *Bulletin*. Mr. Elliott and Mr. Gester, past president, will represent the executive committee at the meeting of the Pacific section this fall at Bakersfield.

Second vice-president Donoghue is keeping in touch with the members in Texas. Third vice-president Rich has visited the Kansas members and gives in this number of the *Bulletin* a geological description of his trip by air with Mr. Elliott from Tulsa to Wichita.

The officers propose by such visits to meet personally more of the members, new members in particular, to keep more intimately informed about the desires and needs of all the members, and to make more available to every member the facilities and services of the Association.

PERIODICAL PUBLICATIONS ON PETROLEUM GEOLOGY

The Association now has at headquarters, 504 Tulsa Building, Tulsa, Oklahoma, a library of forty current publications related to the science of petroleum geology. These periodicals are listed in the department of Reviews and New Publications in this number of the *Bulletin*. The Association receives these valuable journals from eight different countries, in addition to the United States, namely, Austria, Belgium, England, France, Germany, Holland, Peru, and Russia. It is probably in keeping with the facts to say that this list of *Bulletin* exchanges is not surpassed as a comprehensive collection of current periodicals bearing on petroleum geology. This library is a distinct asset to the Association. It should be used freely by our members. It has been suggested that members visiting Tulsa might very profitably avail themselves of the opportunity to consult these scientific periodicals at their Association headquarters.

ASSOCIATION BADGES

Headquarters has a limited number of badges remaining from the supply furnished by the committee on arrangements for the eleventh annual convention held at Dallas in 1926. The bronze metal seal or medal that was a part of the badge may be attached to a strap or ribbon and used as a watch fob. The seal is 1¼ inches in diameter. It bears the crossed geological picks on an oilfield background, above the letters A. A. P. G. Although the Association has adopted no official seal or insignia, several of the members have found this badge desirable for personal wear. Any member in good standing may secure one of these badges from Association headquarters, Box 1852, Tulsa, Oklahoma.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This does not constitute an election, but places the names before the membership at large. In case any member has information bearing on the qualifications of these applicants, please send it promptly to J. P. D. Hull, Business Manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each applicant.)

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AT HOME AND ABROAD

The fifth International Petroleum Exposition at Tulsa, Oklahoma, October 20-29, 1928, will again feature scientific and technical exhibits in the educational building of the exposition. The attendance of geologists and petroleum engineers increases yearly at these unparalleled displays of oil-field equipment.

BASIL B. ZAVOICO, who has been in the geological department of the Sinclair Oil and Gas Company at Enid, Oklahoma, has resigned to engage in the practice of consulting geology.

ROLAND B. PAXSON is now at 1211 Esperson Building, Houston, Texas. Mr. Paxson is general manager and consulting geologist of the McCollom Exploration Company.

A. W. AMBROSE, chairman of the Petroleum Division of the American Institute of Mining and Metallurgical Engineers, announces that the Division will meet at Tulsa, Oklahoma, October 18 and 19, immediately preceding the opening of the International Petroleum Exposition on October 20.

C. A. FISHER of Fisher and Lowrie, petroleum geologists and engineers, Denver, Colorado, is the author of an article on "Rapid Rise of Venezuela in World Oil Production" in the *Yale Scientific Magazine* for March, and reprinted in the *Inland Oil Index* for June 15, 1928.

Oil Field Engineering for June 1, 1928, is a valuable foreign number. RALPH A. LIDDLE, of the Pure Oil Company at Fort Worth, has an article on "Venezuela the Most Rapidly Growing Source of Supply," and JOHN N. STRIGEOFF, senior director of the petroleum industry of the United Socialistic Soviet Republics, is the author of "Russia Successfully Uses Unit Operation System."

H. GERTH has a paper on "Neue Faunen der Oberen Kreide mit Hippuriten aus Nordperu" in the *Leidsche geologische Mededeelingen* for May, 1928, pages 232-41. Reference is made to the paper on "Geology of Northwest Peru" by ARTHUR IDDINGS and A. A. OLSSON in the January number of the *Bulletin*.

J. H. JENKINS, of the Tidal Oil Company at Fort Worth, Texas, has returned from South America.

GEORGE R. ELLIOTT, who has been actively engaged as geologist and petroleum engineer in Oklahoma and California during the past seven years and was recently employed by the Miley Oil Company as petroleum engineer at Long Beach, California, has resigned to return to Canada and is now petroleum engineer in the Department of the Interior, Calgary, Alberta.

H. W. HOOTS, recently with the U. S. Geological Survey in charge of geological work in California, has accepted a position on the geological staff of the Union Oil Company.

C. B. Jones is in charge of geological work for the Union Oil Company of Nevada at Abilene, Texas.

C. A. Heiland, professor of geophysics at the Colorado School of Mines, Golden, Colorado, was in Mexico and California last June. While in Los Angeles and San Francisco, he delivered lectures on geophysical prospecting before the local sections of the American Institute of Mining and Metallurgical Engineers.

John H. Wilson, assistant professor of geophysics at the Colorado School of Mines, presented a paper by C. A. Heiland on "Principles and Recent Successes of Geophysical Methods of Prospecting," before the American Institute of Electrical Engineers' meeting in Denver, Colorado, June 25-29.

R. van A. Mills, petroleum engineer of the Bartlesville, Oklahoma, experiment station of the U. S. Bureau of Mines, has resigned to accept the position of petroleum engineering editor of *The Oil and Gas Journal*, Tulsa, Oklahoma, effective August 1.

Robert B. Bossler is with the Penn Petroleum Company, Exchange National Bank Building, Olean, New York.

C. R. Thomas, chief geologist, Kansas District, Skelly Oil Company, was married Saturday, June 9, to Miss Lucile Reed of Wichita, Kansas.

E. K. Soper, consulting geologist, 839 Roosevelt Building, Los Angeles, California, has been appointed consulting geologist for The Texas Company of California, which recently absorbed the California Petroleum Corporation.

Charles N. Gould, director of the Oklahoma Geological Survey, received the honorary degree of doctor of science, conferred by the University of Nebraska at the commencement on June 2.

Sidney A. Packard, recently of the geological staff of The Texas Company in Colombia, South America, is now in the geological department of the Louisiana Oil Refining Corporation at Shreveport, Louisiana.

F. B. Plummer has been with the Vacuum Oil Company since leaving the Amerada Petroleum Corporation. He is not a consulting geologist, as erroneously stated in the June number of the *Bulletin*. Mr. Plummer's address is 3100 Wabash Avenue, Fort Worth, Texas.

Stanley B. White, geologist with the Transcontinental Oil Company, has been transferred from Stuttgart, Arkansas, to Broken Arrow, Oklahoma.

Lewis G. Mosburg, geologist with the Dixie Oil Company, is now stationed at Shreveport, Louisiana.

The Kansas Geological Society will hold its second annual field conference in the Ozarks of Missouri and Arkansas, Sunday, September 2, to Sunday, September 9, inclusive, instead of August 26 to September 2, as previously planned and announced in the June *Bulletin*. The St. Francois Mountains of Missouri and the Boston Mountains of Arkansas will be visited. All formations from the Mississippian to the pre-Cambrian will be studied, with particular

attention to the Ordovician. For particulars, write to L. W. Kesler, 1007 Union National Bank Building, Wichita, Kansas.

J. J. GALLOWAY, assistant professor of paleontology at Columbia University, New York City, is in the Mid-Continent region this summer, coöperating with the Gypsy Oil Company of Tulsa, Oklahoma, in a study of microfauna of Pennsylvanian formations. Although the immediate results of this work will be of purely scientific importance, it is expected that the report to be published in the *Journal of Paleontology* will have valuable economic bearing.

Foreign Trade Notes No. 200 (June 30, 1928) of the U. S. Bureau of Foreign and Domestic Commerce reports that an important petroleum field has been discovered in Mozambique in the vicinity of the Trans-Zambezian Railway. It is further stated that search for oil continues to show favorable results and that a New York group has offered £5,000,000 for the land exploited.

W. BERNOULLI, recently of Caracas, Venezuela, spent the early summer in the United States. Dr. Bernoulli's present address is 4 Rue Wappers, Antwerp, Belgium.

E. N. MCCORMACK, of the Standard Oil Company of New Jersey, stationed at Iquitos, Peru, S. A., has been in New York for a few months to undergo an operation for appendicitis.

C. S. CORBETT, for three years chief geologist for the Nederlandsche Koloniale Petroleum Maatschappij (Standard Oil Company of New Jersey subsidiary), has resigned from that organization and will return to America from Batavia, Java, in October.

The Geological Society of Northwestern Oklahoma held its regular monthly meeting at Enid on July 7. J. I. DANIELS of the Marland Oil Company of Ponca City, Oklahoma, presented a paper on "The Geology of the Deer Creek Field." WILLIS STORM, A. A. P. G. district representative from Dallas, Texas, attended the meeting. R. S. MCFARLAND, president of the A. A. P. G., as a special guest at the meeting, spoke on the plans and activities of the American Association. Approximately forty-five geologists were in attendance.

PROFESSIONAL DIRECTORY

SPACE FOR PROFESSIONAL CARDS IS RESERVED FOR ACTIVE MEMBERS OF THE ASSOCIATION. FOR RATES, APPLY TO THE BUSINESS MANAGER, BOX 1852, TULSA, OKLAHOMA

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